The 5G Network Solution for Intelligent Traffic: Literature Review and Simulation

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Abstract

As the successor to 4G and LTE networks, 5G is expected to offer more benefits to both business and society. The core characteristics of 5G network includes, but are not limited to, high bandwidth, data rate, network density, and low latency. 5G network is especially useful for activities or operations which require data transmission on a real-time basis. An intelligent traffic system can be beneficial when combined with services utilizing 5G network. The interactions among vehicles and between vehicles and traffic are key components to enhance a traffic light control system. With the help of low latency and high data rates, each vehicle can transfer its information, such as type of the vehicle, speed, destination, position, etc. to the traffic light control system. By obtaining and analyzing this information from all vehicles, the traffic light can be flexible in changing signal phases to create smoother traffic flow and decrease waiting time of vehicles.

This study presents the development of cellular networks as well as the features and limitations of 5G network. It also provides a systematic review of several algorithms used in intelligent traffic systems from three perspectives: isolated traffic light, road network, and eco-driving. Two small traffic scenarios are simulated to obtain different traffic measurements such as waiting time, time loss, speed, and CO2 emission. Finally, this study evaluates and discusses the efficiency of the traffic light system when it can obtain more information as well as the future direction of intelligent traffic research.

Keywords: *5G, Cellular Network, Intelligent Traffic, ITS, Traffic Light, Signaling, Eco-driving, SUMO*

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LIST OF ABBREVIATIONS

API Application Program Interface.

ATL Arterial Traffic Light Algorithm.

C-RAN Cloud Radio Access Network.

CAPC Cell Association and Power Control.

CIVITAS City Vitality and Sustainability.

CORSIM Corridor Simulation.

D2D Device-to-Device.

E2E End-to-End.

EU European Union.

GUI Graphic User Interface.

ICT Information Communication and Technology.

IoV Internet of Vehicles.

ITL Intelligent Traffic Light.

ITS Intelligent Traffic System.

LAN Local Area Network.

LTE Long-term Evolution.

MATSim Multi-Agent Transport Simulation.

MIMO Multiple-input multiple-output.

MITSIMLab MIT simulation-based laboratory.

mmWave Millimeter Wave.

NA Not Applicable.

OAF On-line Algorithm.

QoE Quality of Experience.

RQ Research Question.

SUMO Simulation of Urban Mobility.

Chapter 1

Introduction

As there are more and more vehicles of an ever increasing variety on the street, cities face a crucial challenge of increasing traffic congestion when the expansion of roads is no longer valid. Instead of building more roads or lanes, engineers and scientists work together to design intelligent traffic systems. One of the components which can improve city traffic is the enhancement of traffic infrastructure. Intelligent traffic infrastructure does not only manage vehicles on the road, but also control the communication among vehicles and infrastructure components. Traffic lights, as a traffic component, have evolved from simple automated timers to an intelligent signaling system with various detectors. A smart city uses a connected digital system to improve the traffic flow, reduce traffic congestion and save energy which is beneficial for both the environment and end-users. One of the major problems of the current traffic management system is the limitation of real-time management. However, with the development of 5G network, with high transmission speed and low latency, cities can optimize their networks to provide a real-time situation for traffic management. 5G network can help traffic, specifically traffic light systems, by optimizing the configurations and connections between the traffic lights in the network.

The topic of the concept of 5G network and related applications is becoming more necessary and trendy from both theoretical and practical perspectives. In the Ericsson Mobility Report from June 2019, 5G network deployments are expected to ramp up during 2020, creating the foundation for massive adoption of 5G subscriptions [3]. For example, the European Commission has significantly invested in the promotion of 5G-network projects. From 1990 to 2018, one can identify 222 projects conducted by European Union (EU) members focusing on 5G network technologies . According to the 5G Infrastructure Public Private Partnership, from 2007 to 2013, the EU invested more than 600 million euros to research on 4G-LTE and beyond 4G network. In the Framework Program 7, the European Commission has launched more than 10 projects with an investment of over 50 million euros on the research of 5G technology. Table 1.1 summarizes some EU projects related to the vision of developing 5G network in Europe. Specifically, in the call for Horizon 2020 of the European Commission, the To-Euro 5G Network project is initiated to support and enhance the competitiveness of ICT industry in Europe. The project period ran from the 1st of June, 2017 to the 31st of August 2019 and it was funded for approximately 2.5 million euros. There were several participants in this project from different domains such as universities and leading technology companies. To-Euro-5G Project holds the responsibility for orchestrating the cross-project activities of other applications of the 5G network by setting standards, spectrum, architectures, management, and security. To-Euro-5G project also brings both economic and social benefits to all member states by promoting the development of 5G network and its use. Under the call of To-Euro-5G, there are approximately 50 projects that have been successfully accepted and funded.

Considering these recent developments and the increasing interest in applications of 5G in various domains, the topic of understanding potential use of 5G in increasing the efficiency of traffic light optimization systems was selected for this research work. More specifically, this study aims to answer the following Research Question (RQ):

- RQ1: What are the distinctive features/limitations of 5G mobile technologies currently, and what are the most important existing applications?
- RQ2: How can the benefits of 5G network be utilized in increasing the efficiency of traffic systems?
- RQ3: What are the most important traffic (light) optimization and simulation tools, and what are the most popular implementations?
- RQ4: What is the effect of additional information collected through the use of 5G network on the efficiency of traffic light optimization systems?

Moreover, this study is presented in five chapters. The first chapter is an introduction with motivational examples on the current situation of the 5G network and intelligent traffic systems, together with the research questions. In Chapter 2, the related works and projects on cellular networks and intelligent traffic are discussed in detail. Chapter 3 presents the research methodology used in this study. Chapter 4 describes the simulation of some traffic scenarios and dis-

Project Name	Description	Timeline	Funded Budget
Euro 5G	The Euro-5G project's main objective is promoting the effective and efficient operation and integration of all projects and programs in the 5G domain. It also monitors and facilities 5G-related activities such as conferences and workshops to propose a good solution for the development of 5G infrastructure in the Europe region. The participants include both educational and industrial partners (e.g Eurescom, Nokia, University of Surrey)	1 July 2015 - 31 October 2017	N/A
To-Euro-5G	To-Euro-5G is the second phase of Euro 5G which has the primary objective to support 5G programs. It also improves the competitiveness of Information Communication and Technology industry in Europe. It also extends the partnership to other participants	1 June 2017 - 31 July 2019	Ongoing - N/A
Mobile and Wireless Communication Enablers for 2020 Information Society	This project has the main objective of creating the foundation for the 5G mobile and wireless infrastructure. It also responses to the key challenges of society and opportunities of business. The participants also include a greate amount of partners from both academia and industries such as Aalto University, Ericsson, Nokia, Telecom Italia, etc	1 November 2012 - 30 April 2015	15,855,000 Euros
5th Generation Non-Orthogonal Waveforms for Asynchronous Signaling	This project is led by Fraunhofer Heinrich Hertz Institute and the partnership with other participants in Germany, France, Poland, and Hungary. 5GNOW studies on the design of LTE and LTE-Advanced and its challenges. It also contributes to the 5G standards in the future	1 September 2012 - 28 February 2015	2,490,997 Euros

TABLE 1.1 Sample of 5G projects in EU

cusses the results of the simulations. Finally, the conclusion and future works are discussed in Chapter 5.

Chapter 2

Literature Review

Cellular network is a special kind of wireless technology for mobile phones or electronic devices that require mobile communication. Originally, it was invented by G. Marconi while he attempted to discover a way to transfer a letter "S" by using Morse codes on electromagnetic waves. Later, wireless communication was upgraded to radio, television and satellite transmissions and became more available and applicable in many fields such as telecommunication or entertainment. Following technology development, the data rate, coverage and spectral efficiency in later types of transmission have also expanded to all groups of wireless networks. According to Gupta and Jha [2], wireless networks can be classified based on the indoor/ outdoor usage, circuit/ package switch or licensed/ unlicensed spectrum as visualized in Figure 2.1. Nowadays, 4G Network is widely used around the world and it can handle several user activities seamlessly, such as gaming, web-surfing, streaming or calling, etc. However, as the consequence of the growth of the complexity of humanities problem and cloud computing technology, the need for real-time data is increasing rapidly, which requires new infrastructures. Such technology should be able to solve more critical problems and afford more services in various domains such as health care, education or transportation.

2.1 Cellular Network Evolution

2.1.1 1G to 4G Network

The first generation of wireless networks, 1G, was established in the 1980s with the maximum data rate of 2.4kbps and with a large numbers of disadvantages regarding par capacity or security. In the 1990s, the second generation was introduced, commonly known by its related technology - Global System for Mobile

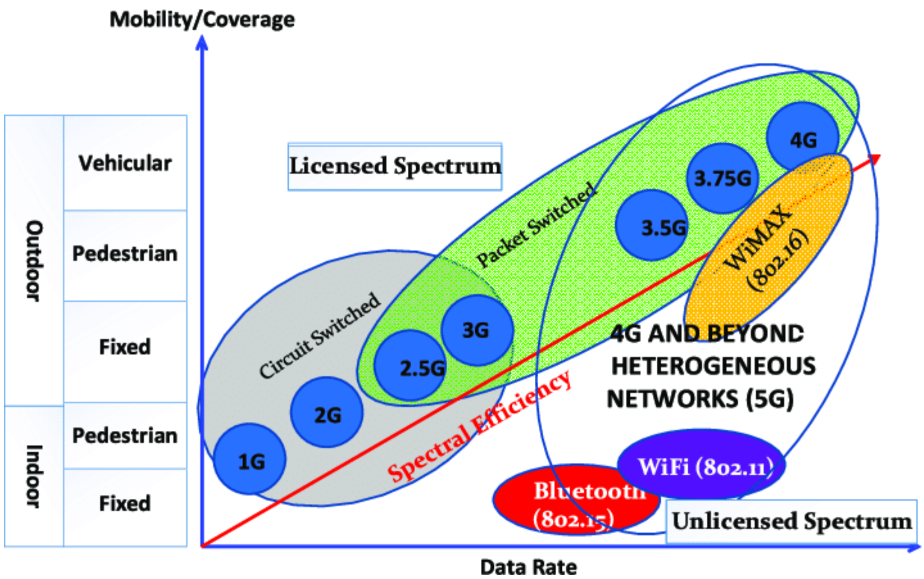

FIGURE 2.1 Evolution of Wireless Technology

Communication (GSM). In the 2G network, GSM can support voice communication, Short Message Service or email. While 1G and 2G networks use only circuit switch for data transmission, 2.5G network uses both circuit and packages switch to provide up to 144kbs of data rate. The new package-switch technology, which was launched in the 2.5G network, was named General Packet Radio Service. The establishment of 3G network in 2000 improved the transmission rate up to 2Mbs and integrated a new service named the Internet Protocol. However, 3G devices had a crucial drawback in terms of energy consumption: they require more power than 2G models. After the success of 3G, 3.75G or Long-term Evolution (LTE) was introduced and it was capable of handling several services that require high speed of data transmission. From this generation on, network technology replaces the circuit switch method by package switch transmission. With the inheritance from both 2G and 3G networks, 4G network can provide a high rate of data transmission and consume less power. In this generation of cellular networks, users can utilize some services like Multimedia Message Service or mobile TV. Some technologies and applications of wireless networks from 1G to 4G are summarized in Table 2.1

Generation	Related Technologies	Data Rate	Frequency Band	Bandwidth	Switching	Application
1G	- Advanced Mobile Phone System - Frequency Division Multiple Access	2.4 kbps	800 MHz	30 KHz	Circuit	Voice
2G	- Global System for Mobile communication - Time Division Multiple Access	10 kbps	850/ 900/ 1800/ 1900 MHz	200 KHz	Circuit	Voice + Data
	- Code Division Multiple Access	10 kpbs		1.25 MHz		
2.5G	- General Packet Radio Services	50 kpbs		200 KHz	Circuit/ Packet	
	- Enhanced Data Rate for GSM Evolution	200 kbps		200 KHz		
3G	- Wideband Code Division Multiple Access - Universal Mobile Telecommunication System	384 kbps	800/ 850/ 900/ 1800/ 1900/ 2100 MHz	5 MHz	Circuit/ Packet	Voice + Data + Video Calling
	- Code Division Multiple Access 2000	384 kbps		1.25 MHz	Circuit/ Packet	
3.5G	-High-Speed Uplink/ Downlink Packet Access	5 - 30 Mbps		5 MHz	Packet	
	-Evolution-Data Optimized	5 - 30 Mbps		1.25 MHz	Packet	
3.75G	Long-term Evolution	100 - 200 Mbps	1.8/ 2.6 GHz	1.4 - 20 MHz	Packet	Online gaming + High Definition Television
	-(Fixed) Worldwide Interoperability for Microwave Access	100 - 200 Mbps	3.5/ 5.8 GHz	3.5 MHz and 7 MHz in 3.5 GHz band 10 MHz in 5.8 GHz band		
4G	-Long Term Evolution Advanced	DL 3 Gbps UL 1.5 Gbps	1.8/ 2.6 GHz	1.4 - 20 MHz	Packet	Online gaming + High Definition Television
	(Mobile) Worldwide Interoperability for Microwave Access	100 - 200 Mbps	2.3/ 2.5/ 3.5 GHz	3.5/ 7/ 5/ 10/ 8.75 MHZ		

TABLE 2.1 Summary of Wireless Network Evolution [2]

2.1.2 5G Network

Fifth-generation or 5G network is the next generation of wireless technologies, and it is expected to be launched in 2020. Currently, there is no formal and precise definition on what exactly a 5G network is, but there is plenty of ongoing research in this domain. According to the expectation, 5G network should be able to overcome some challenges of 4G and LTE networks regard to capacity, data rate, End-to-End (E2E) latency, massive numbers of connections, costs and Quality of Experience (QoE). First, the network capacity of 5G network should be 1000 times larger than the current 4G network. The current cellular network mainly uses the frequency bands below 6 GHz which allows providing the single bandwidth from 5 to 20 MHz. There are two ways to improve the data transmission speed: spectrum utilization and bandwidth expansion. In practice, bandwidth expansion is easier and more direct than the alternative solution. As most of the frequencies under 6 GHz are definitely common and crowded, to increase the bandwidth of the network, in the development of 5G, they consider utilizing a new high-frequency band of the radio spectrum. This spectrum, called "millimeter waves", was currently used for the communication between radars and satellites and it ranges from 30 to 300 GHz. However, millimeter waves also have some limitations. They can not travel through physical obstacles like buildings or trees. Their performance and signal strength are also affected by the weather conditions, such as clouds, rain, and humidity. The second objective of 5G network is to increase the data rate. It is expected to boost the rate to 10 – 100 times higher than 4G/ LTE networks as measured by different metrics such as aggregate data rate, edge rate, and peak rate. The aggregate data rate is the total amount of the data that the network can serve in an area. This metric should be improved about 1000 times in the 5G network. Regarding the edge rate, defined as the worse data rate that end-user can accept when being in the network, the 4G network has an edge rate of 1 Mbps. Therefore, the third goal of 5G network is implementing at least 100 Mbps for 95% users; this is a highly challenging problem from the perspective of technology. Peak rate is another metric and it is commonly used in promoting the cellular network. Peak rate is the best case of data rate that users can expect to obtain. 5G network should have a peak rate of roughly 10 to 20 Gbps. Next, latency is defined as the round-trip to send the package from a place to a destination and return to the sender. The current 4G latency is about 15 milliseconds and 5G network is expected to reduce this number to less than 1 millisecond to support more efficiently cloud-based technologies. Another important expected

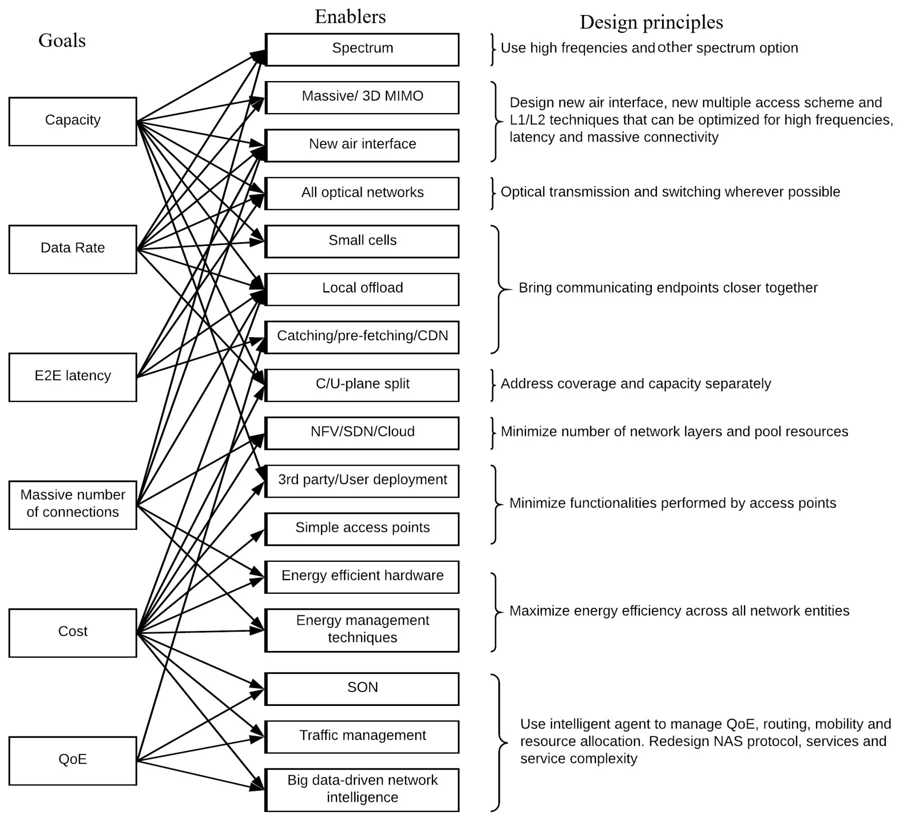

FIGURE 2.2 5G Goals, Enablers and Design Principles

improvement is that there should be a greater number of connecting devices in the network. In other words, the network density should be 10 – 100 times higher. Currently, the 4G network can manage around 2,000 active users per square kilometer while 5G is expected to handle more than 100,000 connecting devices per square kilometer. Due to the core changes in the technology of 5G network, consuming less power is also demanded for the operation. The nature of cell-wise and complete base stations with sleep-mode installation mainly reduces the energy consumption of the device. Moreover, the cost is also kept at a low and sustainable level. Finally, the improvements in data rate, network density and energy consumption are expected to lead to more satisfying user experience when using the network and its related applications. Figure 2.2 summarizes the objectives, enablers and design principles for the development of 5G network [4].

2.1.3 Technologies and Challenges of 5G Network

Millimeter-Wave Solution

As mentioned in the previous section, Millimeter Wave (mmWave) plays a critical role in the Fifth Generation of the wireless network. The currently-used spectrum or "beachfront spectrum" has almost occupied, especially at peak times and markets. Therefore, using a new higher frequency is the only effective way to increase the bandwidth. Fortunately, the high-frequency spectrum from 30 – 300 GHz with the wavelengths from 1 to 10 mm is still available to use. Although mmWave spectrum can have a high quality of propagation, it also creates several challenges relating to its propagation and narrow beam usage. There are three main challenges in the mmWave propagation: path loss, blocking, and absorption. First, the size of antennas is calculated by the wavelength $\lambda = c/f_c$ where f_c is the frequency of the carrier and the antenna aperture is computed by $A = \lambda^2/4\pi$. Therefore, if the frequency increases, the size of antennas will decrease with a factor of f_c and the antenna aperture will shrink with factor f_c^2 , then the free-space power loss (FSPL) will increase with a factor of f_c^2 because $FSPL = (4\pi d^2)/A$. The second challenge of mmWave is blocking issue. In contrast with the low-frequency waves which can travel as a ground wave in diffraction case, the high-frequency waves, especially mmWave are easily diffracted and blocked by obstacles due to the characteristic of electromagnetic radiation – Line-of-sight concept. Another factor that can affect mmWave propagation is the atmosphere and rain absorption. Within 60 GHz band – unlicensed band, the 15 dB/km oxygen absorption is critical, but it becomes less significant in an urban area where the distance of base station is about 200 meters. However, the absorption of atmosphere and air also helps to improve the segregation of each isolated base station. The solution for propagation issues has been investigated and resolved, but the second issue of mmWave which is a narrow beam concept is still new to the communication. The core problem of the narrow beam is the difficulty of formulating a link between users and base stations for access and hand-off by searching for a large number of angular positions. The narrow beam concept also requires a novel transceiver architecture to convert between analog and digital for large bandwidth with energy efficiency.

Multi-tier Heterogeneous Network

Previously we have discussed the limitation of high-frequency spectrum respecting to its travel difficulty through obstacles. The 5G network also requires a high data rate, a large number of connecting devices, and low E2E latency. Therefore, one of the core technologies used to solve these requirements is multi-tier heterogeneous or "small cell" architecture. The current network principally uses single-tier architecture which means that they request a large number of macrocells (high power consumption) to cover the usage of all devices in the range of the station. In contrast with single-tier architecture, the multi-tier heterogeneous uses small numbers of macrocells and large numbers of microcells (low-power consumption). The multi-tier heterogeneous network consists of a small number of macrocells to handle all connections in the network and increase the density of the network in comparison with single-tier type Bhushan et al. [5]. When the size of the cell is reduced, the spectrum can be reused more and as a result, it enhances the efficiency of the network. Moreover, the network can increase the coverage by deploying small cells indoors such as houses, office buildings, vehicles, etc. The indoor base stations allow solving the problem of high frequencies spectrum about transmission limitation through physical objects. Additionally, the Peer-to-Peer, Device-to-Device (D2D) or Machine-to-Machine communications are enhanced by allowing the other nodes (rather than macrocell node) to control the communications. The communication is initiated, and data is transferred directly from a single node to another single node without the agent role of the macrocell node. To handle the heterogeneity, inter-tier and intra-tier communications, 5G architecture needs to apply the interference management. There are several difficulties of interference management relating to cell association, power control, simultaneous association to multiple base station, cooperation/ coordination among multiple tiers [6]. First, the Cell Association and Power Control (CAPC) method is altered in the downlink and uplink communication. The uplink communication focuses on interference mitigation, power consumption reduction of the base station to increase the spectrum efficiency. In the downlink direction, the coverage and traffic load balance of each cell – base station should be improved to retain the quality of communication. Moreover, the transmission power in downlink depends on the battery power of the user device, but it does not vary significantly among users. Therefore, there is no optimal solution for both uplink and downlink and an integrated framework should be able to offer the optimal, or near-optimal solution for both of them. Different from the current CAPC schemes, the 5G network allows one user to connect simultaneously to several base stations. Therefore, the architecture is designed to enhance the system throughput and outage ratio, especially for cell users at the edge. Due to the asymmetry of transmission power in uplink and downlink, the highest downlink can be obtained by connecting with macrocells and the highest uplink can be gained from nearby other microcells. Therefore, the cooperation among the base station in different tiers requires to recognize the user location and channel conditions to decide the communication to improve the spectrum and power efficiency in the network.

Spectrum Sharing Methods

One of the technologies which are implemented in the 5G network to fulfill the requirement of spectrum utilization is spectrum sharing or assignment. Currently, there are two types of spectrum used for the wireless network: licensed and unlicensed spectrum. On one hand, the cellular network uses a licensed one and the frequency bands are fixed on the country and operator basis. The performance of the licensed spectrum is high, but it is inefficient in the low traffic load situation because an operator is denied to use other operator's spectrum resources. On the other hand, the unlicensed spectrum which is used in wireless-LAN technology can operate multiple networks in the same spectrum, but the service quality decreases when the traffic load increases. Therefore, the 5G network can utilize the resources by defining the primary and secondary spectrum switching methods to maintain high-quality service at the normal cases as well as the spectrum efficiency at low traffic load.

Device-to-device (D2D) communication

Another advantage of the 5G network is the enhancement of peer communication such as D2D communication. There are two main levels in 5G network communication which are macrocell-microcell level or device level. On one hand, macrocell levels consist of a base station that communication to devices as an orthodox mobile system. On the other hand, the device level consists of several devices that can be connected and transmitted information among each other. In the case of a device connected directly to the base station, the communication is considered at the macrocell level. Otherwise, if a device is connected directly to other devices or connected to the base station indirectly by using some replaying devices, these communications are classified as operating at the device level. Usually, the communication is operated at a macrocell level, but in the congested network or the device at the edges of the network, the device level communications are created to transmit the data. In D2D or device level communication, the resource allocation can be fully, partially or not controlled by the base station, but the communication from source to destination is successfully initiated. There are four main types of D2D communication (Figure2.3) [7]:

- Device relaying with base station controlled link formation (DR-OC) the source device at the edge of the cell or in poor coverage region can communicate with the base station by relaying the information via other devices. The base station can authenticate the relaying device, encrypt the data and also manage the spectrum allocation among relaying devices to maintain the security, privacy, and smooth transmission.

- Direct D2D communication with base station controlled link formation (DC-OC): the devices communicate and transmit the data directly without passing through the base station. The base station has the role of authenticating devices, initiating communications and maintaining resources for direct communication among devices.

- Device relaying with device controlled link formation (DR-DC): The base station does not involve in the communication from source to destination devices. Source and destination devices exchange the data and communicate via relaying nodes. The authentication, resource allocation, and connection setup are created by devices themselves.

- Direct D2D communication with device controlled link formation (DC-DC): Source and destination devices talk and transmit the data directly to each other without the operation of a base station. These devices also have to create connections, allocate resources and manage interference.

[7] also discusses the pricing challenges in the D2D network. In a traditional network, the D2D communication is free but has low speed and less security for devices. However, in the 5G network, with low latency and high-speed communication, a network operator can consider the charges for D2D communication. Regarding each type of D2D, the pricing should be different due to the variation in controller and direction.

- In DR-OC type, the replying nodes have an important role while they use their resources (batteries, bandwidth) to transmit the data for other devices. Base on the amount of replying data, the operator can either grant some discounts or free services for replying-device owners.

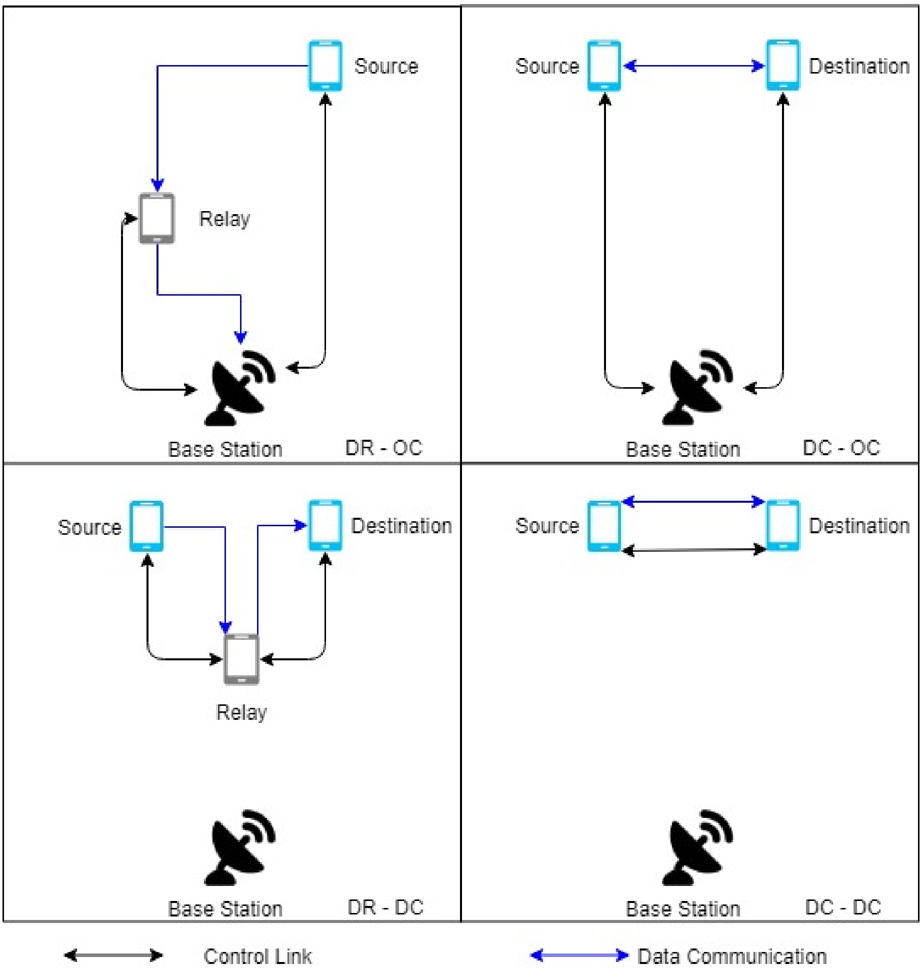

FIGURE 2.3 Four main types of D2D Communication

- In DC-OC type, the main challenge is encouraging the users to retain using D2D services and not using the alternative one such as Wi-Fi or Bluetooth. This is the problem of spectrum usage while operators want the maximum profit and the users want the maximum utility. Operators can implement the Auction scheme to obtain the optimal solutions for revenue – utility problem or game theory to maintain effective resource allocations.
- In DR-DC and DC-DC, there is no control from the operators on communication. Therefore, the operator's profit is not expected.

Massive MIMO

Advanced Multiple-input multiple-output (MIMO) techniques have been applied in the 3G network already. It creates the spatial dimension of the communication between the base station and mobile units through multiple antennas. In the first version of MIMO, single-user MIMO (SU-MIMO) transmits all streams to only one user via the number of antenna. To overcome the problem of SU-MIMO, multiple-user MIMO (MU-MIMO) is introduced to send all streams to multiple users simultaneously by dividing and allocating specific channels to different users. MU-MIMO is currently used in LTE network with two to four antennas per cellphone and up to eight antennas per base station. The number of antenna can be also leveraged to more than hundreds of items so that the number of antenna is much larger than the number of active user at a time. This idea is defined as Massive MIMO or “large-scale” MIMO in other words. Massive MIMO objective is to receive all benefits of MIMO but in much larger scale [8]:

- The capacity can be increased 10 times and the radiated power efficiency can be improved 100 times. In terms of energy efficiency, the larger number of antennas can help to improve by making energy concentrated in a small area due to the coherent superposition of wavefronts. After the shaped signal is sent by the array of antennas, the base station has only a role to make sure that all transmitted wavefronts can add constructively at the intended terminal and randomly at other locations. The improvement of capacity is gained by the spatial multiplexing which uses different antennas and multiple radios to transmit separate segments of a message to the terminal.

- Massive MIMO components are low in terms of cost and power. In a conventional network, the ultra-linear 50-Watt amplifier and a great number of massive items such as large coaxial cables are used. However, Massive MIMO eliminates these expensive items and replaces them with hundreds of low-cost items. By using hundreds of antennas, massive MIMO can mitigate the noise, fading, and hardware imperfection because the signals are combined in the space, so the robustness of the system can be increased against the failure of one or more antennas. Massive MIMO has an exceeding degree of freedom. For instance, with 300 antennas, if there are 30 terminals, the remaining is 270 degrees of freedom. These degrees of freedom or antennas can shape and transmit the signals to the average ratio and constant envelope. Rather, the wavefield is created and sampled at the place where terminals can recognize accurately the signal we want them to observe. Massive MIMO has a characteristic, which is large null spaces, to make it possible. In the null space, almost everything can be engaged without affecting the terminal. The total output Radio Frequency (RF) power which is two steps of lower magnitude is considered as a notable enhancement in power efficiency. As the base station consumes tremendous energy, the reduction of RF power can help the base station to search for replacement energy such as wind or solar power so that they can operate normally in no-electricity locations.

- Massive MIMO allows the decline in the latency on the air interface: latency reduction is one of the important objectives of the 5G network and the main cause of latency is fading. When the signal is transmitted from the base station to terminal, it goes in various paths and its strength is decreased to a very low point due to several phenomena such as reflection and diffraction. If the receivers catch a faded signal, they have to wait for the channels to change until any data can be acquired. Massive MIMO, by using the larger number of antennas with beamforming ideas can prevent the fading dip and its effect on latency.

- Massive MIMO increases the simplicity of multiple access layers: in massive MIMO, the channels harden so that there is no payoff for the frequency domain scheduling. Orthogonal frequency-division multiplexing technique helps each massive MIMO terminal allocate complete bandwidth so that most of the physical layer control redundant can be reduced.

- Massive MIMO strengthens the robustness against unintended human interference and intentional jamming. In the civilian wireless network, intended jamming is expanding and becoming serious as a threat of cybersecurity. Jammers limit the bandwidth so that the spread of information over the frequency is unavailable. Massive MIMO, with a great number of degrees of freedom, can suppress the signal from jammers.

Cloud Radio Access Network

Cloud Radio Access Network (C-RAN) is referred to the system paradigm which is centralized and cloud-computed for the radio access network. C-RAN is an evolved technology that can help to improve both spectral and energy efficiency. In C-RAN architecture, the base station is split into two components: Baseband unit pool (BBU pool) and Remote radio head network (RRH network). BBU pool is served as a centralized processing center for all BBU and each unit is interconnected with high speed and low latency. RRH network is used to link the device to the access point as usual. The connection between BBU pool and RRH is called fronthaul and it is transmitted in optical fiber or mmWave of 5G network. In [9], the C-RAN can improve the deployment process by reducing the construction space and power consumption of base stations as well as speeding the deployment or expansion of the network. Moreover, it also increases the flexibility of resource allocation in scarce situations, mitigates network interference and achieves high performance in both downlink and uplink.

2.1.4 Projects of 5G network in Europe

2.2 Intelligent Traffic

The traffic is increasing in terms of complexity and quantities of transportation, but its infrastructure resources are limited. Therefore, to optimize the overall transportation, intelligence traffic is an approachable and important solution. The intelligent traffic can be interpreted in different aspects, but in this study, we consider only three of them: isolated traffic light control, traffic flow improvement, and energy-efficient driving.

2.2.1 Isolated traffic light control

The isolated traffic light controls traffic flow at a single intersection and it does not communicate with neighboring signal lights. In isolated traffic light, the timing cycle variables [10], which consist of phases, cycle length, offset parameters, and split interval, play a crucial role in control the vehicles flow efficiently:

- Phases: a part of the cycle that allocates the movement of traffic from different directions immediately.
- Cycle length: the time to complete one sequence of signal phases
- Internal: part of the cycle that the traffic participants remain the same.
- Split or phase length: the percentage of the cycle length which is allocated for each signal phase.
- Offset: the time relationship calculated by the difference between a particular point and a reference point in the traffic system

The main goal of isolated traffic control is minimizing the waiting time as well as maximizing the number of vehicle passing through an intersection. Phasing in traffic control is defined by the green signal period for the movement of vehicles from one or more directions. [11] suggest that signal phasing versatility can affect operational efficiency. Variable-sequences phasing or skip-phase capability can enhance the traffic operation while interval change or start-up delay can lower the operation. Moreover, signal phasing needs traffic detection to determine the phasing options. The detectors or sensors can be classified by their technologies or functions [11] and they are summarized in Table 2.2

To enhance traffic performance, the signal control strategies are used together with traffic detectors or sensors. Regarding the vehicle movement and traffic volume density of each leg at the intersection, the actual green time and its request are determined while the maximum and minimum green time are pre-determined in the controller. Faisal Ahmed Al-Nasser [11] suggest that there are three common specific types of traffic actuated controller which can be integrated into the traffic detection technologies:

- Semi-actuated controller: it is used at the intersection of a major street and a minor street in terms of traffic volume difference. The detector is required for minor street only and the detector can request green light for the minor street as well as extending green time up the maximum value due to the presence of vehicles in the minor street. In the major street, the controller can revert to its green phase and remain green as long as there is no vehicle in the minor street.

- Fully-actuated controller: it is used in the intersection of two equal-volume streets. The sensors are required for all legs of the intersection to turn green time and minimize the green interval extension. In case of no vehicle at the traffic such as night time, the controller can remain either the same signal as its last service or change the signal as pre-determined cycle time.

- Volume-density controller: it is similar to a fully-actuated controller but more advanced. It can measure the volume of the vehicle in the green phase and density of queued vehicles in the red phase to enhance the timing operation for an isolated intersection. The controller can either decrease the green extension time or increase the minimum green time by measuring the opposite traffic. To react to a traffic situation accurately, the sensors or detectors must be placed properly and sufficiently before the stop line.

Classification	Name	Description
Technology	Inductive loop detectors	Easy method to track vehicles, but expensive installation
	Compact wireless magnetometers	Less pavement cutting and no physical connection
	Video Imaging Vehicle Detection System	No traffic disruption and pavement degradation; but not accurate due to weather and light conditions
	Digital Wave Radar Detectors	Efficient method to measure the presence and speed of vehicles
	Infrared Detectors	Vehicles and pedestrian movement detection [12]
	Ultrasonic Detectors	Use frequencies reflecting to road and vehicle 's surface to detect vehicle route and presence
	Passive Acoustic Detectors	Use sounds produced by vehicles to detect the energy increase and presence of the vehicle in detection zones
	Combined Technologies	Several above technologies can be used together
Function	Advanced Detection	Locate before the stop line and use to detect vehicle movement before approaching the intersection
	Stop line Detection	Locate at the stop line and it must be highly sensitive to detect slow movement in the traffic zone
	Left & Right turn	Detect vehicles turning left and right
	Counting	Use to count vehicles in each line and lanes by multiple detectors, but the counters might be duplicated
	Violation Detection	Use to detect the violation when the vehicle passes intersection at a red signal
	Truck Detection	Place far away from the intersection to determine the last vehicles passing the intersection so that the truck has sufficient time to cross the intersection

TABLE 2.2 Traffic detection classification

On the other hand, in addition to the usage of physical detectors, traffic light setting is a crucial component to enhance the traffic by finding the optimal solution for the timing of the green and red phases. In the most basic traffic intersection, there are eight direction queues for the traffic, which are North (N), South (S), West (W), East (E), North-West (NW), South-East (SE), West-North (WN) and East-South (ES), are given by number from 1 to 8 in a ready area illustrated by Figure 2.4. The vehicles in the ready area are divided into

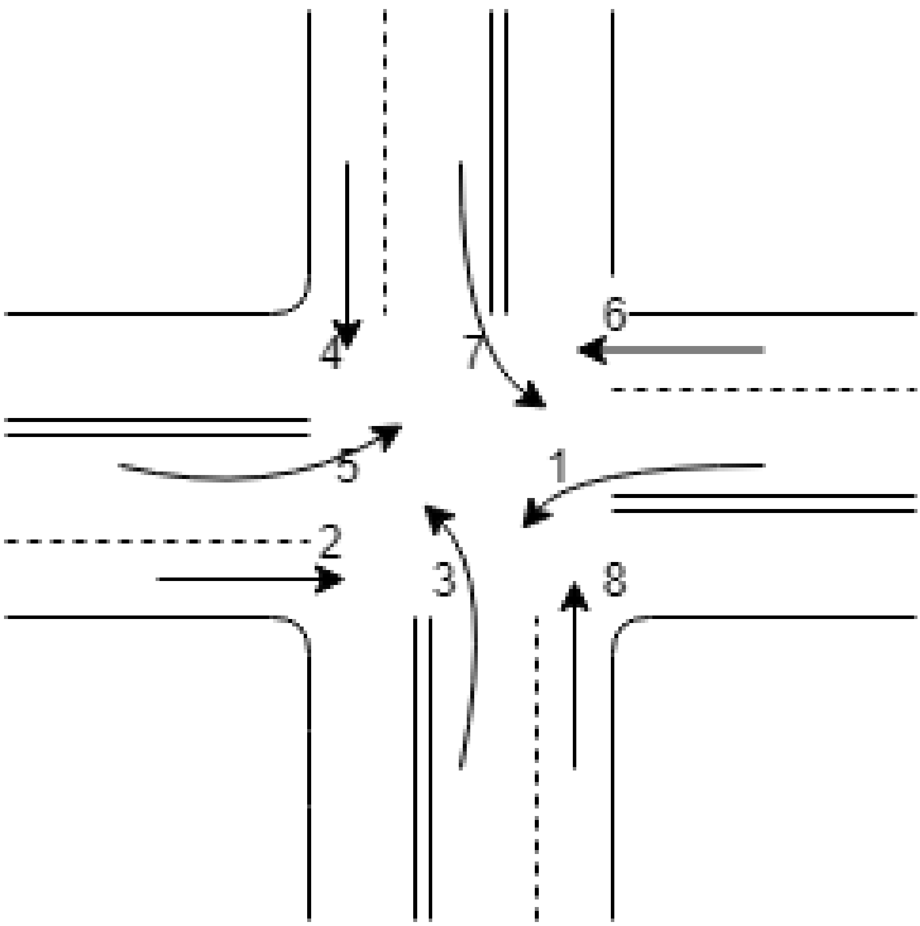

FIGURE 2.4 Basic traffic intersection

different platoons which they all will pass the intersection at the same time when the light is green and we call the green period T. T is computed by $T = \theta + F_d/S_{tf}$ where θ is the delay of the first vehicle, F_d is the distance between the first vehicle and traffic light; and S_{tf} is the average speed of vehicles in that platoon. There are eight options for traffic to pass the intersection at each phase: $P_{15}(1+5)$, $P_{25}(2+5)$, $P_{16}(1+6)$, $P_{26}(2+6)$, $P_{37}(3+7)$, $P_{47}(4+7)$, $P_{38}(3+8)$, $P_{15}(4+8)$. There are only four phases scheduled, but it can cover all traffic flows at the intersection. For example, if phase P_37 and P_48 is selected, there is no need to schedule phase P_38 and P_47 because they have passed the intersection already in selected phases. In [10], an Intelligent Traffic Light (ITL) algorithm is proposed by scheduling all eight traffic flows and beginning with the heaviest-platoon-density phase. Algorithm 1 illustrates the procedure for scheduling the traffic light of the two most dense traffic flows and Algorithm 2 is applied to schedule an appropriate time for a selected phase in ITL. Younes and Boukerche [10] also evaluate ITL algorithm by measuring the performance in some traffic scenarios and comparing it with the previous mechanism (On-line Algorithm (OAF)) which has been claimed to perform better than Vehicular Ad-hoc Network-enabled signal controls in terms of delaying time at the intersection [13]. The performance of ITL is observed that it reduces the queuing time of vehicles at the intersection by 25% than the queuing time by OAF . Moreover, by allowing the highest-density traffic flow to pass the intersection first, the number of vehicle passing the intersection in ITL is computed 30% higher than in OAF.

Besides, a model-based offline optimal control approach was proposed to find the optimal solution for traffic flow over several constraints of traffic such as road density, coupling conditions at the intersection and traffic light modeling [14]. The traffic flow and relating components are formed by a time-dependent mix-integer problem (MIP) to find the optimal solution. For the optimal traffic light setting at the intersection, if the default setting is configured to the green light for all pairs of straight-right-turning lanes and left-turning lanes, the objective value is 66.84. By solving the MIP problem, the object value is 96.63, but the green and red light fluctuate frequently. Therefore, with the new lower and upper bounds setting for the green and red phases, the objective function value is obtained at 88.61, which means that it increases 32.58% in comparison with the default setting. The results in [14] indicate that the optimized configuration for traffic light highly reduces heavy traffic in comparison with the default setting.

Algorithm 1: Intelligent traffic light schedule algorithm

```
Data: TL: traffic light; RA: ready area; d_i: traffic density of flow i in
      RA; t_i: required time for all vehicles in RA at traffic flow i to pass
      the intersection
compute d_i and t_i for all traffic flow inside RA;
while d_i of any of traffic flow at TL > 0 do
    let j the traffic flow with the largest density (d_j);
    let i1 and i2 the traffic flows that can pass the intersection
      simultaneously with traffic flow (j);
    if d_i1 > d_i2 then
        P_ji1 = schedule (j,i1);
        d_i1 = 0.0; t_i1 = 0.0;
    else
        P_ji2 = schedule (j,i2);
        d_i2 = 0.0; t_i2 = 0.0;
    end
    d_j = 0.0; t_j = 0.0;
    Adjust t_k of all other traffic flow in RA;
end
```

Algorithm 2: Time length schedule function

```
INPUT: traffic flows i and j;
if t_i > t_j then
    return t_i
else
    return t_j
end
```

2.2.2 Signalized Road Network Improvement

In practice, it is unlikely to have a single signalized intersection, but a network of roads with multiple intersections. Depending on the distance between intersections, as well as the speed of vehicles, the green time at each junction is set to maintain the smooth flow of traffic and reduce the queuing time on the network. Younes and Boukerche [10] also propose the Arterial Traffic Light Algorithm (ATL) to improve the traffic by cooperating isolated traffic light controlling in the previous section. In ATL, each intersection is installed an ITL to control the characteristics of traffic flow coming to that intersection. Moreover, it also receives the scheduling message (RM) report of neighboring traffic intersections which includes much information such as the number of vehicle coming to the platoon, starting cross time and ending cross time. The traffic light is used by Algorithm 1 first at an isolated intersection to create the schedule phases. Next Algorithm 3 is used to determine the timing cycles by Equation 2.1 which combining both arterial factor (AF_i) and saturation density factor (SDF) as a combined factor (Cf_i). α is also used to consider the importance of these factors.

$$Cf_i = \alpha \times AF_i + (1 - \alpha \times (SDF_i)) \tag{2.1}$$

Algorithm 3: Arterial Traffic Light Controlling Algorithm (ATL)

Data: TL: traffic light; RM: reporting message; N: number of vehicles passing previous TL; S_time: start cross-time of previous TL; E_time: ending cross-time of previous TL; AF: arterial flow; A_time: estimated arrival time; L_time: estimated leaving time; $LCFT$: last cycle finishing time; $NCFT$: next cycle finishing time

use Algorithm 1 to schedule initial cycle phases of TL;
send RM of AF to next TL on the street;
when TL_1 receives RM from TL_2, it calculates;
$A_time = S_time + distance(TL_1, TL_2)/S_tf$;
$L_time = E_time + distance(TL_1, TL_2)/S_tf$;
if $A_time < NCFT$ **then**
    while $CurrentTime < A_time$ **do**
        use Algorithm 1 to schedule the next cycle phases of TL and do not consider AF;
    end
    use Equation 2.1 to calculate Cf_i of each competing flow i;
    while Cf_i *of any traffic flows at* $TL > 0$ **do**
        let j the traffic flow with maximum combined factor (Cf_i);
        let $i1$ and $i2$ the traffic flows that can pass the intersection with traffic flow j;
        if $Cf_i1 > Cf_i2$ **then**
            $P_ji1 == \text{ART-schedule } (j, i1)$;
            $Cf_i1 = 0.0; t_i1 = 0.0$;
        else
            $P_ji2 == \text{ART-schedule } (j, i2)$;
            $Cf_i2 = 0.0; t_i2 = 0.0$;
        end
    end
else
    $Cf_j = 0.0; t_j = 0.0$;
    use Algorithm 1 to schedule the next cycle of phases of TL;
end

Similar to Algorithm 1 in isolated traffic, the ATL algorithm also needs scheduling function (Algorithm 4) to report the arrival and departure time to the next traffic signal. Younes and Boukerche [10] also compares the performance of ATL algorithm with previous algorithms such as Random mechanism and

ART-SYS [15]. ART-SYS has the highest for the delay of each traffic light and ATR-algorithm-applied traffic is lower 10% of a total delay than ART-SYS. However, in comparison with the Random mechanism, ATR's total delay is 1% higher. In terms of throughput of the traffic, ATL algorithm increases 7% in comparison with ART-SYS while it decreases 2% in comparison with the Random mechanism. The reason for the result difference comes from the priority of the arterial flow. ATL defines the priority based on several conditions while ART-SYS mainly consider it only and Random mechanism ignores it completely. As the final performance evaluation, ATL algorithm could help to increase the traffic fluency and throughput as well as reduce the total delay of the traffic light.

Algorithm 4: Arterial Schedule (ART-schedule)

Data: AF: arterial flow; $A_t ime$: estimated arrival time; $L_t ime$: estimated leaving time

if i *is an* AF **then**
    if $t_i < (L_t ime - A_t ime$ **then**
        $t_i = L_t ime - A_t ime$
    end
end
if $t_i > t_j$ **then**
    return t_i
else
    return t_j
end

The previous algorithm (i.e ATL) aims to make a controller for each traffic node and analyze the condition of the vehicle to determine the traffic cycle and length-time. However, this approach, which is known as "traffic-light-based controller", has some disadvantages due to the great number of the possible situations at each traffic light and the lack of communication to vehicles. To overcome these obstacles, Wiering et al. [16] propose to use another approach (named "TC-1"), which is "car-based controller" to reduce the cumulative waiting time of all cars in road network before exiting the infrastructure. TC1 bases on the reinforcement learning algorithms in which agents need to learn the policy by obtaining feedback about specific pairs of state-action from the interacting environment without knowing transition P and reward functions R in advance. In TC1 approach, each car information such as position, speed, and destination is modeled and its waiting time will be predicted so that the traffic light can determine after combining all information. In this approach, the number of state of each car is feasibly computed based on the current position, direction, destination and if the information of waiting time for each car is estimated, the route for its travel is possible to optimize. A car-based value function is also introduced in [16] to compute the time of each car which will wait until it reaches the destination in both red or green light at intersections. Each car has the following components: current traffic location (*node*), destination (*des*), position in the queue (*place*) and the direction (*dir*). All these components denote the car-based value $Q([node, dir, place, destination], action)$ or shortly $Q([n, d, p, des|, L$ with *action* (or L) is the traffic light decision (either green or red). The average waiting time for a car is also denoted by $V([n, d, p, des])$. Given the current condition of traffic, the decision can be made for each intersection by Equation 2.2.

$$A_j^{opt} = agrmax(A_j) \sum_{i \in A_j} \sum_{(n,d,p,des) \in queue} Q([n, d, p, des], red) - Q([n, d, p, des], green) \quad (2.2)$$

To calculate A_j^{opt}, we need to compute function Q and V by using state transition probabilities as well as reward functions.

- State transition probability:
  $P([node, dir, place], L, [new_node, new_dir, new_place])$
- Reward function: $R([node, dir, place], L, [node, dir, place]) = 1$ if car stays the same or $R = 0$ if car moves forward

Q and V functions is computed in Equation 2.3 and 2.4 with the initialized value of 0.

$$Q([n, d, p, des], L) = \sum_{n',d',p'} P([n, d, p, des], L, [n', d', p']) (R([n, d, p], L, [n', d', p')]) + \gamma V([n', d', p', des]) \quad (2.3)$$

$$V([n, d, p, des]) = \sum_{L} P(L|[n, d, p, des])Q([n, d, p, des], L) \quad (2.4)$$

with γ is the discount factor to bound Q-values and $P(L|[n, d, p, des])$ is the probability that the traffic light is green or red for a car. [16] also perform a simulation for their approach (TC-1) and compare with several traffic-controller algorithms such as simplified versions of TC-1, bucket algorithm, best first, Random mechanism, ACGJ-3, Relative longest Q in three different experiments: large infrastructure, co-learning and inner-city and obtain the following results:

- The first experiment is conducted to study the performance of these algorithms in high traffic load and complex road networks. TC-1, as a result, outperforms all other algorithms and the "co-learning" feature further improves the TC1 performance.
- The second experiment is used for studying the improvement of co-learning in traffic by optimizing the travel route. As a result, TC-1 reduces waiting time by 50% in comparison with the random shortest path algorithm.
- The third experiment is conducted to evaluate the performance in a city-like structure surrounded by ring roads. In this experiment, TC1 again outperforms other algorithms and decreases the waiting time more than 25%

By combining the traffic light and other components of traffic, the Internet of Vehicles (IoV) was introduced to enhance the traffic and it is widely used in many smart-city infrastructures [17]. IoV is originally developed by the Internet of Things technology which refers to an interconnected system of many objects, devices, networks, and information. IoV requires communication among vehicles (Vehicle-to-Vehicle - V2V) or between vehicles and other objects or devices (Vehicle-to-Road - V2R, Vehicle-to-Human - V2H and Vehicle-to-Sensor - V2S). Kumar et al. [1] propose a new IoV approach for traffic management which includes four stages: map segmentation and graph conversion, ant colony optimization algorithm, traffic intensity calculation, and pheromone update and they are represented in Figure 2.5. In map segmentation and graph conversion stage, the map is separated into different same-size segments and they are converted to a graph which includes sets of nodes and links: $G_N = (O_N, L_N)$ with O_N is set of nodes and L_N is set of links. The routing table R_{ti} is maintained and updated by the number of node i: $R_{ti} = G_{Ni} = (O_{Ni}, L_{Ni})$. In ant colony algorithm, the procedures of forward and backward ant are used to identify the best route from the current location to the destination. The number of maximum vehicle on the road can be calculated by

$$Max\_NV_{ij} = \frac{LL_{ij}}{(L_v + \Delta L)} \times NL_{ij} \tag{2.5}$$

Where, LL_{ij} is length of road, NL_{ij} is number of roads between node i and j, ΔL is averaged distance between two cars, L_V is averaged length of vehicles.

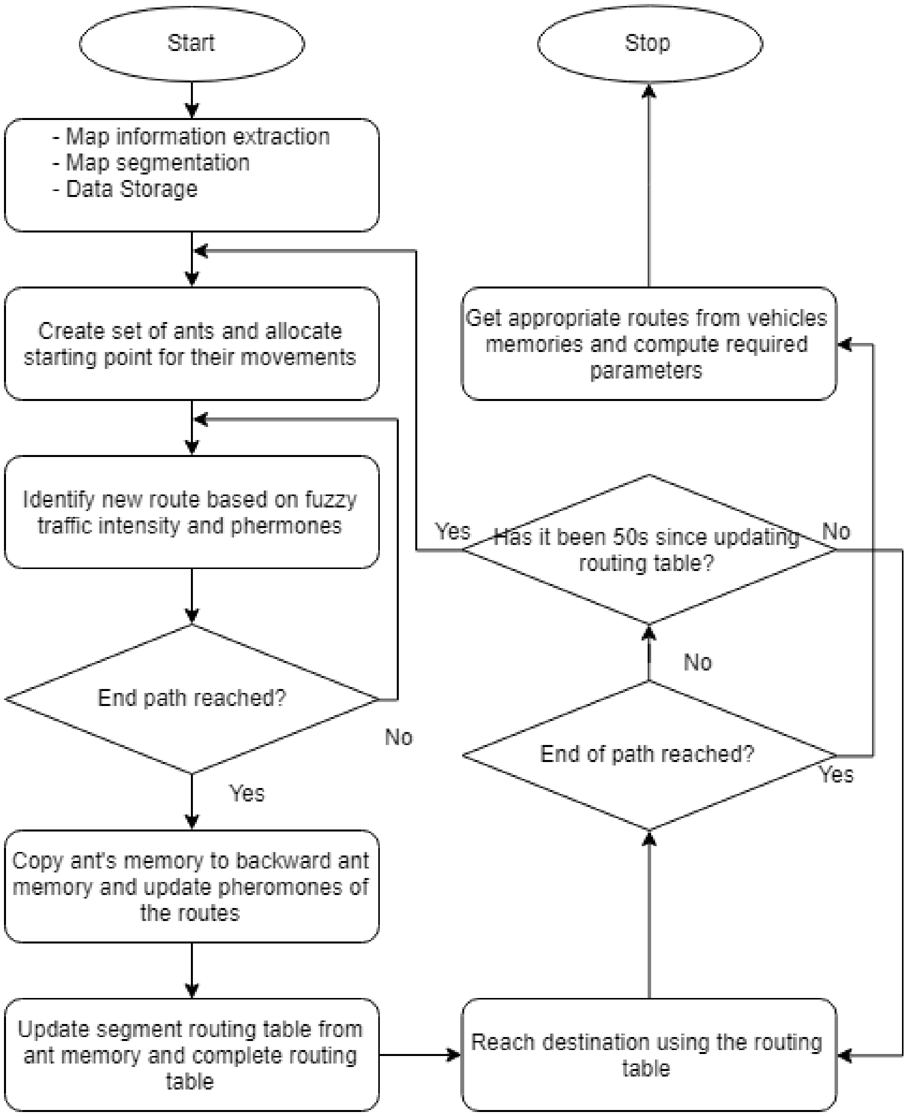

FIGURE 2.5 Workflow of Kumar et al. [1] process

Linguistic Variable	Fuzzy Membership Function
Very Low	(0,0,0.25)
Low	(0,0.25,0.5)
Medium	(0.25,0.5,0.75)
High	(0.5,0.75,1)
Very High	(0.75,1,1)

TABLE 2.3 Lines and Traffic input parameters

Next, the density of Vehicle (D_{ij} is calculated by,

$$D_{ij} = \frac{NV_{ij}}{Max\_NV_{ij}} \tag{2.6}$$

Then, the movement to the new place of ant is defined by forwarding ants as below:

$$p_{ij}^{k}(t) = \left\{ \begin{array}{c} \dfrac{a(\delta_{ij}) + b(1-\eta_{ij})}{\Sigma_{h \notin tabu_j} a(\delta_{ij}) + b(1-\eta_{ij})} \times \left(\dfrac{1}{1+\dfrac{1}{N_j}} \right) \text{ if } j \notin tabu_k \\ 0 \text{ otherwise} \end{array} \right\} \tag{2.7}$$

Where δ_{ij} is pheromone value of an ant moving from node i to node j, η_{ij} is instantaneous state of fuzzy value on the connection from i to j, a is importance weight of δ_{ij}, b is importance weight of η_{ij}, $tabu_k$ is set of nodes linked to node i that ant k has not visited, N_j is number of neighbors for node j. The traffic intensity is considered as an output variable in Table 2.3 after computing two input parameters such as Lines and Traffic in Table 2.4. The traffic intensity is defined by $\overline{y_i} = 0.01, 0.15, 0.3, 0.5, 0.7, 0.85, 1$ and the average defuzzifier is defined by $\eta_{ij} = y_i^* = \dfrac{\sum_{i=1}^{20} \overline{y_i} \times \mu_{Lines \cap Traffic}}{\sum_{i=1}^{20} \overline{y_i}}$ with $\mu_{Lines \cap Traffic} = min(\mu_{Lines}, \mu_{Traffic})$.

Finally, the change of pheromone values is computed by

$$T_{ij}^{new} = (1-p)T_{ij}^{old} + \sum_{k=1}^{m} \Delta_{T_{ij}^{k}} \tag{2.8}$$

Where $P \in A[0,1]$ is pheromone evaporation value and m is the number of node in the same segment.

Kumar et al. [1] also compare the IoV algorithm with other shortest path selection algorithms such as Dijkstra, Kruskal and Prim Algorithms and claim it as better performance in terms of both average travel time and waiting time.

Linguistic Variable	Fuzzy Membership Function
Very Low	(0,0,1)
Low	(0,1,3)
Medium Low	(1,3,5)
Medium	(3,5,7)
Medium High	(5,7,9)
High	(7,9,10)
Very High	(9,10,10

TABLE 2.4 Intensity output variable

2.2.3 Eco-driving

Instead of evaluating the traffic enhancement on the average waiting and travel time, eco-driving is another perspective that can be improved by intelligent traffic. The ultimate objective of eco-driving is minimizing the energy consumption of vehicles and emissions from a point to another location by given full knowledge of traffic lights timings. The most common and useful factors that drivers can affect the eco-driving skills are speed, acceleration, deceleration, route choice, idling and vehicle accessories [18]. First, the power of vehicle electric motors is formulated while the traffic light is determined by defined cycle time, phase time and offset. The sub-optimal strategy is proposed to solve this optimization problem and it is validated with Dynamic Programming [19]. The sub-optimal strategy consists of three steps:

- The velocity pruning algorithm is used to handle the green phase portion at each intersection to decrease the search space of available green lights. By doing so, the vehicle can reach the final destination within the speed limit by stopping at a minimal number of intersections.
- After running Pruning Algorithm, the number of available green phase is reduced, but there are still many possible paths from the origin to destination. The next step of the proposed strategy is to measure approximately the energy consumption of all possible trajectories by constructing a weighted directed acyclic graph and applying Dijkstra's algorithm to find the optimal path with the lowest energy consumption.
- Finally, the problem becomes convex and it can be optimized by using the crossing times at each intersection.

As a result, the energy cost approximation is close to each other in both Dynamic Programming and Sub-optimal algorithm with the overall average deviation between these two algorithms (in the case of five intersections and two initial speeds) is 0.23 second. However, Dynamic Programming costs 2.5 hours per path to find an optimal solution while the proposed strategy costs only 1.2 seconds with 3 nodes/ green phase for all steps to find optimal crossing time. By using the same approach, Ozatay et al. [20] propose an algorithm strategy to optimize the vehicle speed in multiple traffic-light intersections so that the fuel consumption can be reduced. The vehicle longitudinal dynamics and fuel consumption model are introduced to form the optimization problem. This optimization problem can be solved by both analytic and numerical solutions. The fuel consumption differences in these methods are almost the same. However, the computation time of the numerical solution is significantly larger than the analytic solution.

2.2.4 Traffic exiting software and implementation

As the rising concerns relating to public safety and serious traffic congestion, intelligent traffic solutions are growing with the expectation of being worth about USD 30.7 billion by 2023. The intelligent traffic solutions can be segmented into hardware, software, and service, but the software segment is growing rapidly by applying advanced and complex algorithms to improve the traffic. There are several key providers including Thales (France), Siemens (Germany), Garmin (Switzerland), Kapsch TrafficCom (Austria), TomTom International (Netherlands), Cubic (US), Q-Free (Norway), EFKON (Austria), FLIR Systems (US), and Denso (Japan). Large corporations such as Thales or Siemens provide comprehensive traffic solutions for smart cities. They cover many aspects of traffic from "on-road" challenges such as traffic and signal controllers, traffic detectors, enforcement and tolling to "back-road" challenges such as traffic control centers, interface and priority systems. They also manage not only vehicles on the road, but also other types of transportation such as metro, train, and tram. Moreover, these systems can transform real-time traffic data to useful information and insights for agencies to analyze and understand the patterns as well as end-user behaviors so that they can consider an appropriate strategy for the traffic. In comparison with the completed solution from giant firms, City Vitality and Sustainability (CIVITAS) is a project co-financed by the EU to promote the cleaner and better traffic in Europe [21]. Mobility management and Intelligent Traffic System (ITS) are two of the CIVITAS core dimensions. Since 2002, CIVITAS has implemented successfully 35 ITS projects in 23 cities in Europe. Table 2.5 briefly summarizes some ITS solutions in the world.

Solution	**Provider**	**Description**
Siemens Intelligent Traffic Systems	Siemens (Germany)	The solution provides the comprehensive solution for many challenges such as ”On the road” (traffic controllers, signal head, traffic detectors, enforcement and tolling.) and ”Strategic Management” (traffic centers, interfaces and systems)
Urban Mobility	Thales (France)	Thales provides IT-based critical solution to manage all kinds of transportation activities such as signaling solutions for urban mobility, communication, and supervision for urban mobility, and ticket and revenue collection
Kapsch TrafficCom	Kapsch (Austria)	Traffic Com is a one-stop solution to make reliable, safe, efficient and comfortable urban traffic. It covers many fields such as tolling, traffic management, smart urban mobility, traffic safety, and security, and connected vehicles
CIVITAS	Europe	CIVITAS is an innovative solution funded by EU and it has implemented over 800 urban transport measures and solutions in over 80 cities across Europe. The projects mainly focus on 10 thematic areas: Car-Independent Lifestyles, Clean Fuels & Vehicles, Collective Passenger Transport, Demand Management Strategies, Integrated Planning, Mobility Management, Public Involvement, Safety & Security, Transport Telematics, Urban Freight Logistics.
Acyclica	FLIR (USA)	Acyclia platform uses raw traffic data to detect traffic patterns, analyze the real-time congestion and provide information and insights to government and agencies.

TABLE 2.5 Intelligent Traffic Software

Chapter 3

Research Methodology

As typical research in business, quantitative and qualitative analysis approaches are often recommended to answer the research question. The quantitative approach's objective is to transform the data in raw form into insightful information. It uses different graphs and statistics to analyze raw data. The quantitative approach can be conducted by the following steps:

- Preparing, inputting and checking data: Data can be obtained from both primary and secondary sources and its type should be defined before coding and inputting into the computer. Missing values and errors are also checked carefully to avoid false conclusion.
- Exploring and presenting data: Data can be presented by different forms of visualization such as tables, diagrams, charts or plots.
- Describing data using statistics: the descriptive statistic is used to describe and compare variables on two aspects: central tendency and dispersion.
- Examining relationships, differences and trends by using statistics: two groups of statistical testing are used to conduct the significance or hypothesis testing based on the research questions. Non-parametric statistics are designed for the testing when data is not in normal distribution form or data is not categorical. In contrast, parametric statistics are designed for numerical data.

In contrast with quantitative data, the qualitative data is more ambiguous, complex and subjective. It is principally derived from words, not numbers. Therefore, the qualitative analysis is conducted through the use of conceptualization by the following aspects:

	Qualitative Research	Quantitative Research
Objective	It is used to gain the understanding of reason, motivation, and opinion	It is used to quantify the problem and examine the relationship between variables
Research Type	Exploratory	Conclusive
Approach	Subjective, ambiguous	Objective, unambiguous
Method	Unstructured such as interview, group discussion	Structured such as surveys, observations, questionnaires
Data	Unmeasurable, mostly in textual verbal form	Measurable, mostly in categorical and numerical forms

Table 3.1 Comparison of Qualitative and Quantitative Research

- Deciding analysis approaches: there is a variety of approaches that can be used to process the analysis: generic, inductive and deductive approaches.
- Preparing data for analysis: Because qualitative data can exist in many forms which may include oral or hand-written forms, it should be converted into word-process text for further analysis. Transcribing data and scanned document techniques might be useful for this conversion.
- Aids to help analysis process: interim/ event/ document summaries, self-memos, research notebook or reflective diary.

Table 3.1 compares the differences between qualitative and quantitative analysis approaches. Both approaches are widely used for different purposes of research in business and social sciences. Moreover, if the research topic relates to the information system, simulation can also be used as a research tool. Bratley et al. [22] define that simulation is like a process of "driving a model of a system with suitable inputs and observing its corresponding outputs". Base on the purpose of simulation, Hegselmann et al. [23] identifie five categories for the simulation:

- a technique to gain more details of a system
- a heuristic tool to develop a hypothesis
- a substitute for an experiment to execute the research experiment.
- a tool for researchers to support practical lab experiment
- a pedagogical tool to explain a process

These classifications of simulation can be applied to four fundamental research phases that are discover, justify, build and evaluate. Simulation is a helpful tool for both descriptive and prescriptive research when a suitable simulation is used at the right activities in the research cycle. Table 3.2 reveals an overview of possible applications for simulation classifications in different research phases.

In the market, there are many traffic simulation tools which either focus on the detail of vehicle behavior or traffic management in a large area. There are several common and widely-used tools such as SUMO, MATSim, CORSIM, and MITSIMLab:

- SUMO stands for Simulation of Urban Mobility and is developed by the German Aerospace Center [24] [25]. SUMO can be used to model all components of traffic such as roads, vehicles or pedestrians. It also supports various APIs that provide interaction with other tools and frameworks such as Traffic Control Interface [26] or Python/ Java API. Moreover, it is also broadly used in many research projects relating to Intelligent Traffic System. The major research topics using SUMO are about vehicular communication, route choice, dynamic navigation, traffic light algorithms, and evaluation of traffic surveillance system [27].
- MATSim stands for Multi-Agent Transport Simulation and is developed by Polytechnic of Zurich. MMATSim offers a framework for demand-modeling, agent-based mobility-simulation (traffic flow simulation), re-planning, a controller to iteratively run simulations as well as methods to analyze the output generated by the modules. MATSim is currently used to simulate the traffic in Switzerland, Germany, Indonesia, and Canada[28].
- CORSIM stands for Corridor Simulation and is developed by The Federal Highway Administration - a division of the United States Department of Transportation. CORSIM is a comprehensive microscopic traffic simulation, applicable to surface streets, freeways, and integrated networks with a complete selection of control devices (i.e., stop/yield sign, traffic signals, and ramp metering). It simulates traffic and traffic control systems using commonly accepted vehicle and driver behavior models. CORSIM combines two of the most widely used traffic simulation models, NETSIM for surface streets, and FRESIM for freeways. CORSIM has been applied by thousands of practitioners and researchers worldwide over the past 30 years and embodies a wealth of experience and maturity[29].
- MITSIMLab stands for MIT simulation-based laboratory and is developed by MIT in MIT Intelligent Transportation Systems Program. It is used for evaluating the impacts of alternative traffic management system designs at the operational level and assisting in subsequent design refinement. Examples of systems that can be evaluated with MITSIMLab include advanced traffic management systems and route guidance systems[30].

In this study, the traffic is simulated by SUMO to gain more understanding of the intelligence traffic model and the relations between individual vehicles and traffic components.

Phase / Simulation	**Discover**	**Justify**	**Build**	**Evaluate**
Technique	NA	Obtain understanding and confirmation of theories and models	Obtain understanding of used artifacts and grounding the design of proven theories	NA
Heuristic	Discover new models, hypotheses and theories	NA	NA	NA
Substitute	NA	Confirm or disconfirm theories	NA	Evaluate the artifact
Tool	Identify experiment for evaluation		Identify experiment for evaluation	
Pedagogical Use	NA	NA	NA	NA

Table 3.2 Classification of simulation and research phase

Chapter 4

Simulation

4.1 Introduction to SUMO

Simulation of Urban Mobility or SUMO is an open-source road traffic simulation package under the license of Eclipse Public License V2. SUMO consists of the following features [24]:

- Simulation
- Network import
- Routing
- High portability
- High interoperability through the usage of XML-data-only
- Open-source

It can be used to simulate wide ranges of traffic topics in research projects such as routing, congestion, signal evaluation, traffic forecast or implementation of traffic center. Besides vehicle interaction, the movement of the pedestrian with vehicles also can be simulated in SUMO. SUMO also allows for creating a variety of measures of traffic. In this study, SUMO GUI - the graphical user interface version is used to simulate traffic and evaluate the traffic signal in a specific area. SUMO GUI generates the simulation by combining several XML files that are used to define the network, vehicles, routes characteristics. In SUMO-GUI, it is allowed to locate different objects and examine their parameters only. There is no modification of traffic simulation in SUMO-GUI.

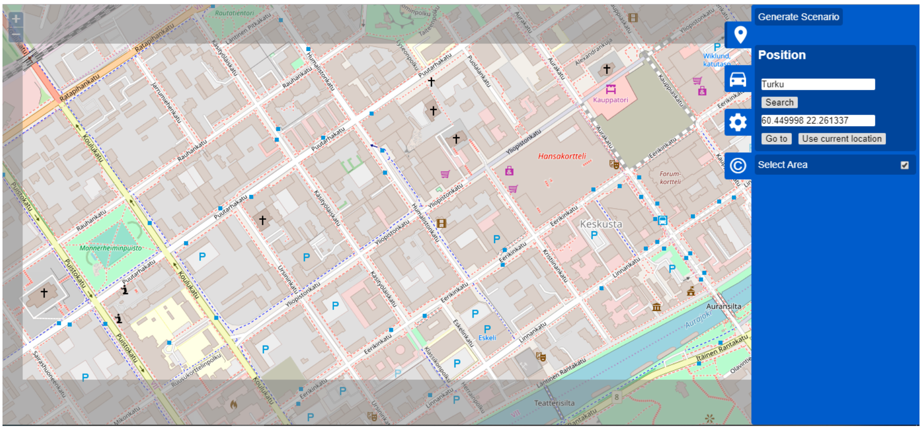

FIGURE 4.1 OSM Web Wizard function of SUMO

4.2 Traffic simulation

To construct the traffic layout for the simulation, we use one of SUMO functions that is OSMWebWizard to convert an area of Turku city map to the simulation layout. SUMO automatically creates the land for vehicles, traffic lights at intersections and traffic rules. Figure 4.1 indicates the interface of OSMWebWizard. After generating the basic traffic layout, SUMO produces some basic XML files for constructing more objects in the maps which include the following:

- osm.net.xml is used to define network elements such as land, routes, intersections, traffic lights, etc.
- osm.passenger.trips.xml is used to manage personal vehicle characteristics which include departure and arrival position, time, speed, route, etc.
- osm.bus.trips.xml is used to manage bus characteristics that cover departure and arrival position, time, speed, route, etc.
- osm.truck.trips.xml is used to manage truck characteristics which include departure and arrival position, time, speed, route, etc.
- osm.poly.trips.xml is used to construct the building, parking areas, rivers, etc.
- osm.sumocfg is used to manage the input, output and other configurations for the simulation.

To perform the simulation for the traffic in this study, we modify osm.net.xml to change the types of traffic light whether it is static (fixed phase of the signal)

FIGURE 4.2 OSM XML file of SUMO

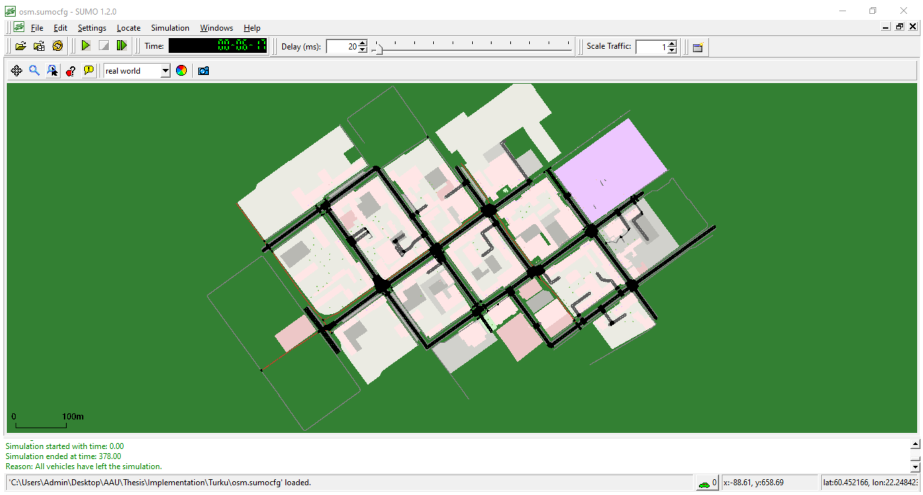

FIGURE 4.3 SUMO-GUI

or actuated (flexible phase of the signal based on the vehicles at the intersection). Osm.passenger.trips.xml, osm.bus.trips.xml, and osm.truck.trips.xml are used to produce the vehicles on the road and their characteristics, and in our simulation, we limit the number of vehicle and their departure positions. Figure 4.2 illustrates parts of the XML files used in SUMO. After configuring all XML files, the main simulation is called to run. As indicated in Figure 4.3, we can run, pause and locate each object of traffic simulation in SUMO-GUI. SUMO also supports a variety of output, but in our scope, we only concern the following outputs:

- average trip waiting time (computed in second): the average time of all vehicles in the simulation when they have to stop and wait to move due to the traffic signal or congestion.
- average trip time loss (computed in second): average time of all vehicles which are lost when they have to move slower than the ideal situation

network: Parameter

Name	Value
updates per second	0.00
avg. updates per second	12719.80
avg. trip length [m]	754.80
avg. trip duration [s]	194.55
avg. trip waiting time [s]	77.12
avg. trip time loss [s]	126.04
avg. trip depart delay [s]	7.10
avg. trip speed [m/s]	3.88
nodes [#]	144
edges [#]	544
total edge length [km]	16.89
total lane length [km]	22.15
network version	1.10

FIGURE 4.4 Parameter Trip Summary

- trip speed (computed in meter/second): average speed of all vehicles after completing their trips in the area.
- Total CO2 emission (computed in milligram): the emission produced by each vehicle at each time frame. The total CO2 emission of the trip is computed by the multiplication of average CO2 emission for all vehicles (mg/s) and the total time of completing trip (s).

The average trip waiting time, time loss and speed can be obtained in the parameter summary of trip in SUMO-GUI in Figure 4.4 while the CO2 emission has to be computed manually at each time after obtaining the detailed report of CO2 emission for each vehicle at each time frame in Figure 4.5

```xml
<emission-export xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance" xsi:noNamespaceSchemaLocation="http://sumo.dlr.de/xsd/emission_file.xsd">
    <timestep time="0.00">
        <vehicle id="veh0" eclass="HBEFA3/PC_G_EU4" CO2="2185.40" CO="5.52" HC="0.07" NOx="0.68" PMx="0.01" fuel="0.94" electricity="0.00" noise="63.06" route="
        <vehicle id="veh1" eclass="HBEFA3/PC_G_EU4" CO2="2624.72" CO="164.78" HC="0.81" NOx="1.20" PMx="0.07" fuel="1.13" electricity="0.00" noise="55.94" route
        <vehicle id="veh10" eclass="HBEFA3/PC_G_EU4" CO2="2624.72" CO="164.78" HC="0.81" NOx="1.20" PMx="0.07" fuel="1.13" electricity="0.00" noise="55.94" rout
        <vehicle id="veh11" eclass="HBEFA3/PC_G_EU4" CO2="2165.86" CO="8.11" HC="0.08" NOx="0.68" PMx="0.01" fuel="0.93" electricity="0.00" noise="62.79" route=
        <vehicle id="veh13" eclass="HBEFA3/PC_G_EU4" CO2="2510.68" CO="0.00" HC="0.00" NOx="0.74" PMx="0.01" fuel="1.08" electricity="0.00" noise="65.74" route=
        <vehicle id="veh15" eclass="HBEFA3/PC_G_EU4" CO2="2624.72" CO="164.78" HC="0.81" NOx="1.20" PMx="0.07" fuel="1.13" electricity="0.00" noise="55.94" rout
        <vehicle id="veh16" eclass="HBEFA3/PC_G_EU4" CO2="2106.12" CO="21.39" HC="0.14" NOx="0.70" PMx="0.01" fuel="0.91" electricity="0.00" noise="61.60" route
        <vehicle id="veh2" eclass="HBEFA3/PC_G_EU4" CO2="2624.72" CO="164.78" HC="0.81" NOx="1.20" PMx="0.07" fuel="1.13" electricity="0.00" noise="55.94" route
        <vehicle id="veh20" eclass="HBEFA3/PC_G_EU4" CO2="2624.72" CO="164.78" HC="0.81" NOx="1.20" PMx="0.07" fuel="1.13" electricity="0.00" noise="55.94" rout
        <vehicle id="veh21" eclass="HBEFA3/PC_G_EU4" CO2="2157.28" CO="9.41" HC="0.09" NOx="0.69" PMx="0.01" fuel="0.93" electricity="0.00" noise="62.66" route=
```


FIGURE 4.5 Detailed CO2 Emission Report

4.3 Traffic scenario

In this study, we consider two scenarios of traffic: trip scenario and intersection scenario. In trip scenario - Scenario 1, we investigate the efficiency of a traffic light when it receives information about the current traffic rather than no information. A part of Turku area is selected to convert into SUMO object (Figure 4.6). There are various vehicles departing from random positions with different routes and they can either pass through the intersection with a traffic light or free intersection with no traffic light. In this scenario, an area of Turku city is captured and transformed into SUMO objects. The land, routes, signal control, and traffic rules are automatically defined randomly. There are seven traffic lights in this scenario. The number of truck and bus is set fixed while the number of car is set increasingly in Scenario 1A and 1B. The cars, buses, and trucks' departure speed is 0 m/s while the positions and routes are initiated randomly. The default emission types of vehicle are HBEFA3/PC_G_EU4 (gasoline-driven passenger car Euro norm 4) for passenger vehicle, HBEFA3/Bus (average urban bus for all fuel types) for buses, and HBEFA3/HDV (average heavy-duty vehicle for all fuel types) for trucks. The traffic lights are set to either static (Scenario 1A) or actuated (Scenario 1B) to investigate the efficiency of the signaling type. In Scenario 1C, while the number of truck is constant, the number of car and bus varies from 10 to 50 and from 5 to 15 respectively. The Table 4.1 lists down all the parameters used in Scenario 1.

In the second scenario, an intersection with only one traffic light is focused as in Figure 4.7.Table 4.2 indicates all parameters for simulation. In this scenario, the traffic light is set to be actuated which means its phase can be prolonged based on the incoming traffic. There are only 100 cars passing through the intersection from right to left. The number of car joining in the traffic management system varies from 0 to 100 (corresponding from 10% to 100% of total cars). The cars depart at the same position, same time and travel the same route with the departure speed of maximum speed limit and the emission type of HBEFA3/PC_G_EU4. In this scenario, we examine the effectiveness of actuated traffic when there is a part of cars joining in the intelligent traffic system.

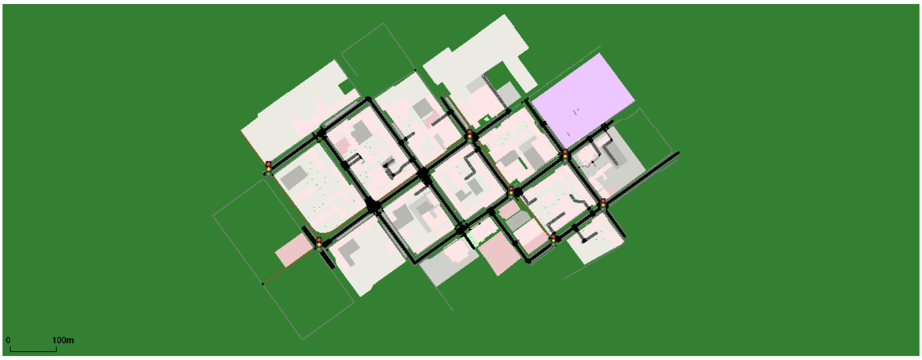

FIGURE 4.6 Scenario 1 Map

Scenario	**1A**	**1B**	**1C**
Total Vehicles	25 - 105		20 - 70
Car	10 - 100 (increased by 10)		10 - 50 (increased by 10)
Bus	10		5 - 15 (increased by 5)
Truck	5		5
Traffic Type	Static	Actuated	Static and Actuated
Measurement	Waiting time, time loss, speed and CO2 emission		

TABLE 4.1 Scenario 1 - Summary

Scenario	**2**
Number of Vehicle (Car)	100
Percentage of intelligent car	0% - 100%
Traffic light type	Actuated
Measurement	Waiting time, time loss, speed and CO2 emission

TABLE 4.2 Scenario 2 - Summary

FIGURE 4.7 Scenario 2 Map

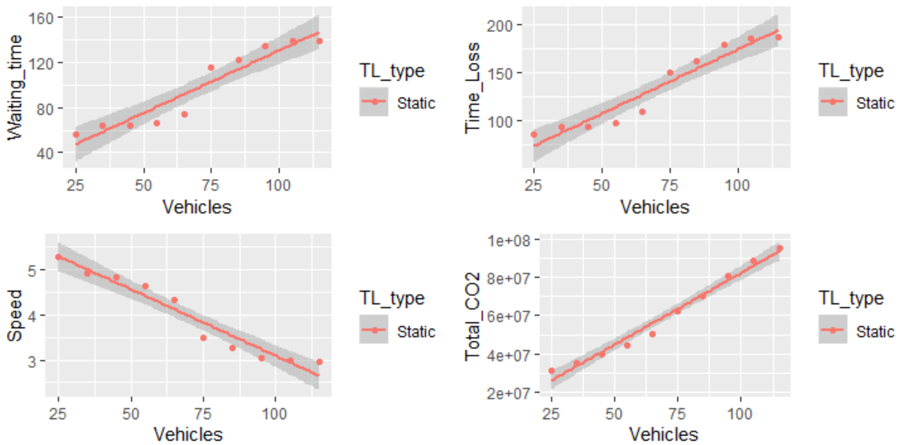

FIGURE 4.8 Static Traffic Light Plot

4.4 Evaluation and Discussion

4.4.1 Scenario 1

After simulating Scenario 1, we obtain an interesting result. When the traffic light is set to static type when more cars engage in the simulation, the average of waiting time and time loss increase while the average speed decreases. The total CO2 emission of the network grows as the number of car rises. On average, all vehicles must wait 92.26 seconds and lose 133.994 seconds while completing trips in the scenario with the average speed at 4.998 m/s. The measurement for static signal control is visualized in Figure 4.8. Similar to static traffic light, the actuated traffic light also produces the same result for average waiting time, time loss and total CO2 emission. When the number of car increases, these

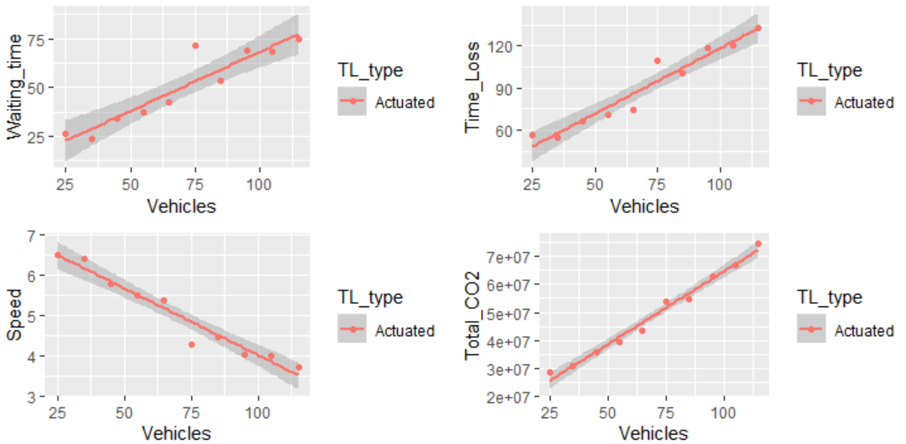

FIGURE 4.9 Actuated Traffic Light Plot

Traffic Type	Average of Waiting_time	Average of Speed	Average of Time_Loss	Average of Totcal_CO2
Actuated	50.07	5.00	90.58	49,040,618.43
Static	97.26	3.98	133.99	59,821,635.09

FIGURE 4.10 Scenario 1 Result Summary

measurements significantly decrease. The average speed of actuated traffic also has the same pattern as the one in static traffic. The summary of simulation results in Scenario 1A and 1B is indicated in in Figure 4.10 and 4.11 . As we can observe from the table, in average, the actuated traffic light helps to reduce around 48.2% the average waiting time for the traffic, 32.4% of the average time loss and 21.1% the total CO2 emission by vehicles for the whole trip in comparison with the static traffic light. For waiting time and total CO2 emission, actuated signaling control has a higher impact on the traffic rather than static type. When the number of vehicle is 25, the average waiting time of actuated light is 30.15 seconds less than static light. However, when the number of vehicle reaches 115, the difference rises to 63.58 seconds. The total CO2 emitted by 25 vehicles in actuated traffic is around 28.308 million grams and is about 9.8% less than the total CO2 emission in static traffic. The total CO2 emission has been conducted to investigate the relations between CO2 emission and speed[31] [32] [33] or congestion at traffic intersection [34] [35] [36]. The percentage difference increases to around 17.1%. The difference between actuated-static traffic light in terms of time loss also rises when more vehicles join in the traffic network.

In Scenario 1C, Figure 4.12 and Figure 4.13 indicate the average waiting time and time loss of all vehicles in both actuated and static traffic light. The

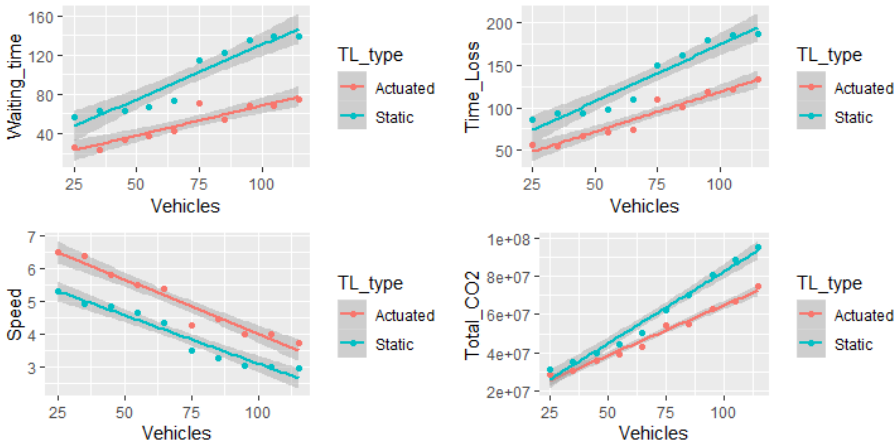

FIGURE 4.11 Scenario 1 comparison plot

average waiting time and time loss change significantly when the number of car and bus increases in actuated traffic while there is a notable change in static traffic. However, it is not true in terms of speed and total CO2 emission. When there are more cars and buses in the network, the average speed is likely to decrease (Figure 4.14) and the total CO2 emission is likely to increase in both actuated and static traffic (Figure 4.15). In conclusion, actuated traffic light, which receives information from vehicles, can enhance notably the traffic movement in terms of waiting time, total loss, speed, and total CO2 emission when there are more participants in traffic.

4.4.2 Scenario 2

In this scenario, we run the simulation ten times and increase the number of vehicle participating in the intelligent traffic system. Figure 4.16 represents the relations between the number of vehicle joining intelligent traffic system and traffic metrics. When there are more cars sent information to the traffic lights, their waiting time and time loss can be reduced significantly and their average speed increases. In this simple simulation, because there is only one flow of traffic, the faster vehicles can complete the trip which means smaller waiting time and time loss, the less CO2 they emit. Therefore, in the simulation of one actuated traffic light, the number of participant in the intelligent network has linear relationships with waiting time, time loss, speed, and CO2 emission. When there is 10% of vehicles transferred information to traffic light, the average waiting time is 7.38s, time loss is 13.87s, speed is 5.37 m/s and total CO2 emission is

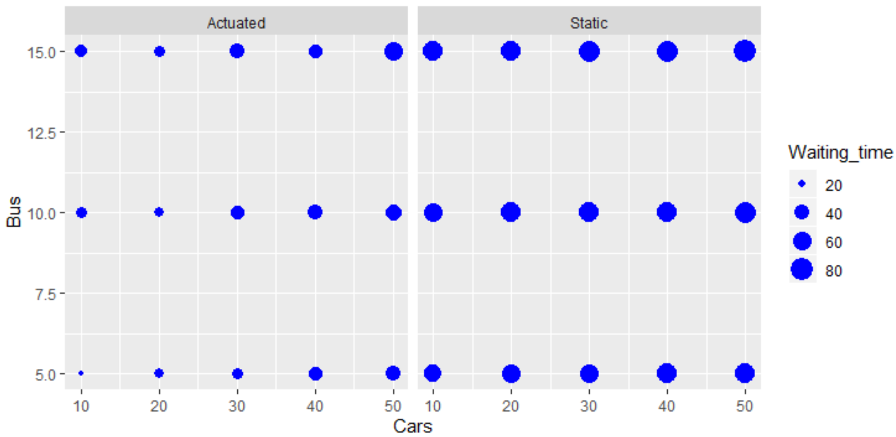

FIGURE 4.12 Scenario 1C - Average Waiting Time

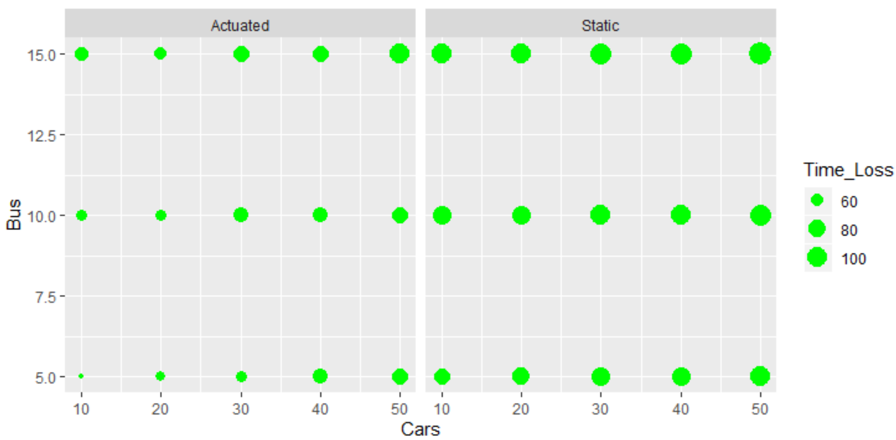

FIGURE 4.13 Scenario 1C - Average Time Loss

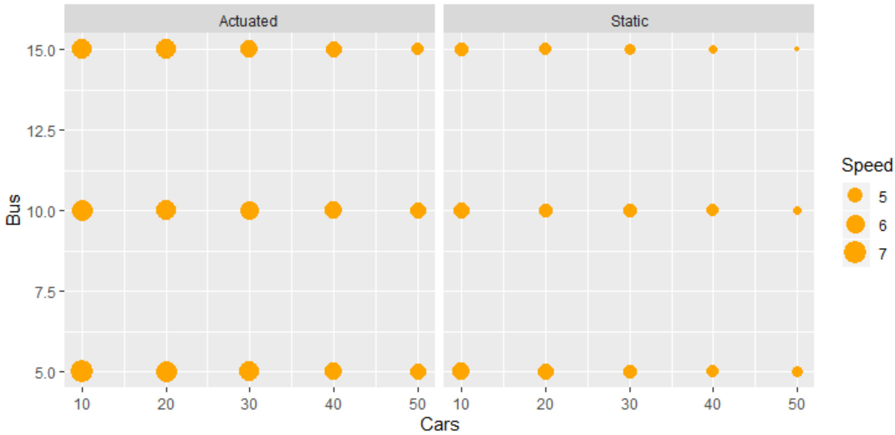

FIGURE 4.14 Scenario 1C - Average Speed

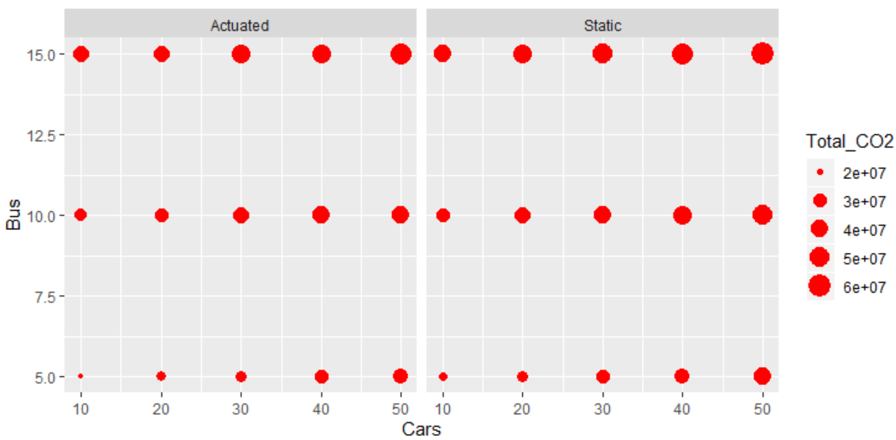

FIGURE 4.15 Scenario 1C - Average Total CO2 Emission

57,542,57 grams. If the percentage of that vehicle rises to 80%, the waiting time reduces 60% to 2.12s, time loss reduces 47% to 6.33s, speed increases 34% to 7.33 m/s and the total CO2 emission reduces 12%. In conclusion, if the traffic light can receive more real-time information from individual vehicles or more intelligent cars joining the network, it can improve the traffic system by managing the signal phases more efficiently and effectively.

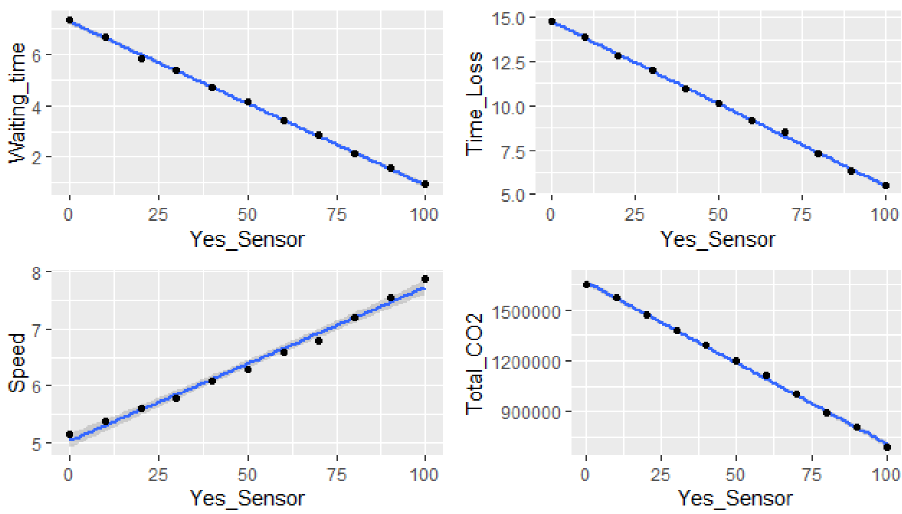

FIGURE 4.16 Scenario 2 plot

Chapter 5

Conclusion

With the development of technology and the requirement of human activities, the 5G network can play a critical role in the technology road-map of many countries and regions. One of its applications is improving the efficiency of traffic by optimizing the traffic light operation. Based on the literature review and simulation result, the answers to our research questions are collected.

RQ1: What are the distinctive features/limitations of 5G mobile technologies currently, and what are the most important existing applications?

The 5G network has overcome the challenges of 4G or LTE networks and significantly enhance the network operation by introducing new technologies such as millimeter-waves, multi-tier heterogeneous network, spectrum sharing, D2D communication, and massive MIMO. Millimeter waves can replace the fully-occupied spectrum in current cellular networks which can create the space for bandwidth expansion. However, mmWaves cannot maintain their power while traveling due to the limitation of path loss, blocking, and absorption. Spectrum sharing is a solution to utilize both licensed and unlicensed spectrum by providing the switching method between this spectrum. Massive MIMO and multi-tier heterogeneous are two core technologies in the 5G network. They provide the new architecture of cellular network by using a great number of microcells and a small number of macrocells to improve energy consumption as well as data rate. However, the installation and placement of microcells or antennas become more complex in the 5G network. Device-to-Device communication is also another feature of the 5G network when it allows faster data transmission among devices without the existence of a base station in the middle. Nonetheless, the authentication, routing algorithm and benefit of operators can cause some problems when there is direct communication without network operator management. Ultimately, the objective of the 5G network is providing communication with low latency, high data rate, and high network capacity. With these advantages, the 5G network can be enabled for many applications in different industries. For example, in education, healthcare and entertainment, the large bandwidth and low latency of 5G network can significantly enhance the video streaming for Augmented Reality/ Virtual Reality applications such as online classroom, surgery support or event streaming. Another example of a 5G network application is a smart city. It can improve the connection among several objects such as traffic light, toll, public transportation, traffic enforcement so that their communication is established smoothly and stably on a real-time basis.

RQ2: How can the benefits of 5G network be utilized in increasing the efficiency of traffic systems?

Traffic system is a collection of a large number of traffic objects which requires real-time data transmission. D2D communication can be applied in the traffic system to provide low latency transmission for information flow among traffic objects, especially the vehicles and traffic lights. It assists the traffic management system, in general, to receive more information to analyze and adapt its operation to real situations. The operation enhancement is principally evaluated by the waiting time, queuing time and average speed of vehicles in an isolated traffic light and road network. Isolated traffic light, as a core component of intelligent traffic, has been investigated to improve its operation. In comparison with a traditional traffic light which has fixed signal phases regardless of the current situation of traffic, the flexible and situation-based traffic light can receive more information from the incoming vehicles. The more information it receives, the better traffic effectiveness it can enhance. Second, when the isolated traffic light is improved, the network of roads with multiple traffic lights and traffic flow can also be optimized by the real-time information exchange among single traffic lights. Moreover, better traffic operation also provides the eco-driving by minimizing the energy consumption and emission of vehicles on the streets.

RQ3: What are the most important traffic (light) optimization and simulation tools, and what are the most popular implementations?

The intelligent traffic system becomes popular now and it receives much attention and investment from both public and private sectors. On one hand, Siemen (Germany), Thales (France) and Kapsch (Austria) have developed and commercialized their solutions for intelligent traffics. These companies provide a comprehensive solution to all kinds of traffic activities such as signal controllers, public transport, tolling, traffic control center, etc. On the other hand, many projects from governmental expenditures such as CIVITAS (EU) and Acyclica (US) have been applied in several cities and certain domains of traffic management only. Besides these completed solutions, the traffic simulation tool is also a great contributor to the research in intelligent traffic. There are several of them which are widely used around the world. Some of them are developed by education institutes such as MATSim by Polytechnic or Zurich or MITSIMLab by MIT while some of them are developed by public agencies such as SUMO by German Aerospace Center or CORSIM by US Department of Transportation. Among these tools, SUMO is the most popular package and it is widely used for traffic simulation in various research topics.

RQ4: What is the effect of additional information collected through the use of 5G network on the efficiency of traffic light optimization systems?

In this study, we have simulated two scenarios to support the efficiency of actuated traffic in four measurements which include average waiting time, time loss, speed, and CO2 emission. From the result in the previous section, in a whole traffic network, when the traffic light can receive information about the upcoming vehicle, in other words, the traffic signaling phase depends on the real situation, the average waiting time, time loss, speed and CO2 emission are all improved. Moreover, if there are more vehicles sending information to traffic light, the traffic efficiency is also enhanced.

Finally, although the traffic system can be optimized by providing more information to single traffic light, the management of traffic flow and interactions among traffic light have not been investigated. Our measurement is also limited to four metrics, but there are many other metrics for the traffic such as the completed-trip time, brake-hold frequency or COx, NOx, noise emission or fuel consumption. These areas are also important in an intelligent traffic system and they can be included in future research.

Appendix

Vehicles	**Cars**	**Bus**	**Truck**	**TL_type**	**Waiting_time**	**Time_Loss**	**Speed**	**Total_CO2**
25	10	10	5	Actuated	26.4	56.46	6.48	28,308,509.94
35	20	10	5	Actuated	23.71	54.53	6.39	30,694,352.34
45	30	10	5	Actuated	34.13	66.4	5.78	35,695,410.41
55	40	10	5	Actuated	36.96	71.37	5.5	39,323,255.19
65	50	10	5	Actuated	42.23	74.38	5.36	43,286,763.62
75	60	10	5	Actuated	71.44	109.55	4.28	54,008,477.02
85	70	10	5	Actuated	53.56	100.17	4.47	54,674,646.47
95	80	10	5	Actuated	68.94	118.88	4.01	62,797,901.40
105	90	10	5	Actuated	68.32	120.78	3.99	66,787,678.89
115	100	10	5	Actuated	74.99	133.26	3.72	74,829,189.04
25	10	10	5	Static	56.56	86.49	5.3	31,378,622.76
35	20	10	5	Static	63.4	93.36	4.93	35,350,188.59
45	30	10	5	Static	63.58	94.08	4.83	40,076,446.77
55	40	10	5	Static	66.67	97.25	4.65	44,303,227.07
65	50	10	5	Static	73.82	109	4.33	50,196,184.79
75	60	10	5	Static	114.97	149.32	3.5	62,435,240.47
85	70	10	5	Static	121.75	161.31	3.28	70,286,077.55
95	80	10	5	Static	134.74	178.66	3.03	80,457,049.17
105	90	10	5	Static	138.54	184.79	2.98	88,607,856.38
115	100	10	5	Static	138.57	185.68	2.96	95,125,457.31

TABLE 5.1 Scenario 1A 1B - Simulation Data

Vehicles	Cars	Bus	Truck	TL_type	Waiting_time	Time_Loss	Speed	Total_CO2
20	10	5	5	Actuated	18.05	45.1	7	19,752,747.01
30	20	5	5	Actuated	22.6	50.16	6.54	22,976,189.63
40	30	5	5	Actuated	25.13	53.53	6.29	25,894,928.65
50	40	5	5	Actuated	35.36	67.93	5.57	31,074,259.95
60	50	5	5	Actuated	40.67	72.99	5.36	34,447,488.30
25	10	10	5	Actuated	26.4	56.46	6.48	28,308,509.94
35	20	10	5	Actuated	23.71	54.53	6.39	30,694,352.34
45	30	10	5	Actuated	34.13	66.4	5.78	35,695,410.41
55	40	10	5	Actuated	36.96	71.37	5.5	39,323,255.19
65	50	10	5	Actuated	42.23	74.38	5.36	43,286,763.62
30	10	15	5	Actuated	29.67	63.44	6.15	36,145,164.39
40	20	15	5	Actuated	25.32	58.64	6.2	38,775,331.50
50	30	15	5	Actuated	40.28	74.36	5.48	44,691,503.50
60	40	15	5	Actuated	36.52	72.72	5.46	47,339,405.87
70	50	15	5	Actuated	55.66	95.92	4.68	55,012,490.79
20	10	5	5	Static	48.95	75.55	5.62	21,700,081.86
30	20	5	5	Static	54	80.96	5.24	25,439,153.02
40	30	5	5	Static	58.42	86.86	4.98	30,184,653.55
50	40	5	5	Static	63.78	92.65	4.72	34,457,116.97
60	50	5	5	Static	65.07	96.89	4.58	39,189,775.00
25	10	10	5	Static	56.56	86.49	5.3	31,378,622.76
35	20	10	5	Static	63.4	93.36	4.93	35,350,188.59
45	30	10	5	Static	63.58	94.08	4.83	40,076,446.77
55	40	10	5	Static	66.67	97.25	4.65	44,303,227.07
65	50	10	5	Static	73.82	109	4.33	50,196,184.79
30	10	15	5	Static	63.83	97.81	4.95	40,486,155.89
40	20	15	5	Static	66.75	98.79	4.78	43,605,452.70
50	30	15	5	Static	72.62	106.43	4.51	50,149,692.24
60	40	15	5	Static	75.38	110.94	4.32	55,300,705.49
70	50	15	5	Static	81.04	117.33	4.15	61,319,043.87

Table 5.2 Scenario 1C - Simulation Data

Vehicles	No_sensor	Yes_Sensor	Percentage	Waiting_time	Time_Loss	Speed	Total_CO2
100	100	0	0%	7.38	14.77	5.16	5,851,471.27
100	90	10	10%	6.69	13.87	5.37	5,754,257.46
100	80	20	20%	5.83	12.83	5.6	5,596,181.12
100	70	30	30%	5.37	12.05	5.79	5,502,776.06
100	60	40	40%	4.72	10.95	6.08	5,458,164.21
100	50	50	50%	4.15	10.16	6.28	5,381,119.95
100	40	60	60%	3.4	9.16	6.58	5,324,932.59
100	30	70	70%	2.86	8.48	6.8	5,166,465.69
100	20	80	80%	2.12	7.33	7.19	5,047,738.08
100	10	90	90%	1.54	6.33	7.54	5,014,739.20
100	0	100	100%	0.94	5.5	7.87	4,917,076.85

Table 5.3 Scenario 2 - Simulation Data

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